FOOT FUNCTION AND NORMAL CORONAL PLANE RANGE-OF-MOTION AT THE ANKLE-JOINT-COMPLEX.

DAVID M HOLLAND

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Department of Engineering

University of Durham

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Foot function and normal Coronal plane range-of-motion at the ankle-joint-complex.

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ABSTRACT.

An investigation was carried out into normal coronal plane range-of-motion at the ankle-joint-complex. To facilitate this, an accurate and reliable measurement rig was designed. The range of motion at the ankle joint complex was measured in one hundred subjects of both sexes (mean age 24.6, range 18-49) by applying a torque of 4Nm to an axis which deviated medially by 16 degrees. The results showed a mean equilibrium position of 19.5 degrees inverted, a mean total range of motion from the equilibrium position of 66.15 degrees, and a mean total inversion value from horizontal of 64.4 degrees.

Three further experiments were carried out. The purpose of these was to examine diurnal variation in range of motion (n = 7), to examine the effect of rig axis position on the range of motion (n = 15), and to look for any difference in ankle joint complex range of motion in those patients with symptoms proximal to the ankle, and those with symptoms distal to the ankle (n = 20). Significant differences in measurement for each variable at each time interval for all subjects were observed, and significant differences in range of motion were found for each measurement, apart from inversion, when movement around different axis orientations were compared. Similar inversion values are due to the difference in equilibrium position between an axis bisecting the foot and an axis which deviates by 16 degrees medially, and a comparison of inversion values from horizontal show a mean difference of 27 degrees. No significant difference in range of motion was found in a comparison study of patients with symptoms distal and proximal to the ankle joint complex.

The findings of this study have important implications both for clinical practice in the field of foot and ankle treatment, and for further research into ranges of motion at the ankle joint complex.

ACKNOWLEDGEMENTS

I would like to thank Tony Unsworth for his continued support throughout this project. I would also like to thank Brian Blackburn for his advice and assistance in the design and building of the rig. Peter Craig and Simon Smith for advice with statistical tests and Julian Minns and Jimmy Cunningham for their help in the early days.

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GLOSSARY.

ANATOMICAL TERMINOLOGY (Whittle 1996)

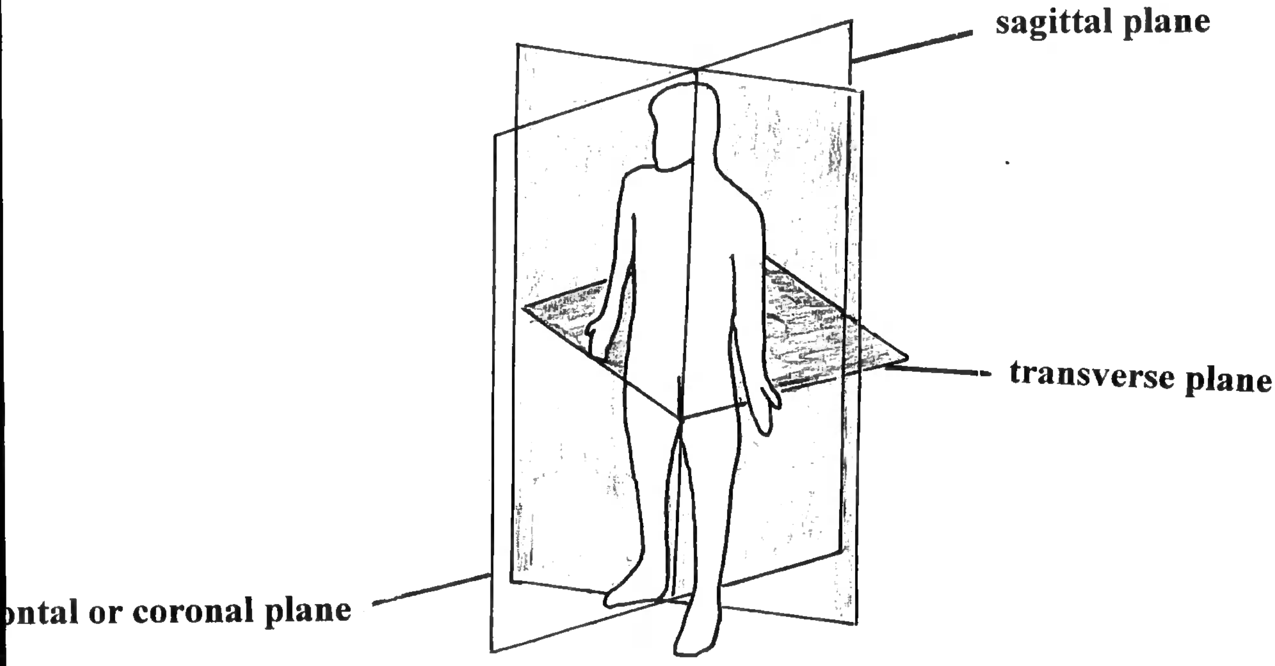
Sagittal plane - is any plane which divides part of the body onto right and left portions.

Frontal plane - also called the Coronal plane. Divides the body into front and back portions.

Transverse plane - divides a body part into upper and lower portions.

Inversion - of the feet - brings the soles together.

Eversion - of the feet - causes the soles to point away from the mid-line.



Reference planes of the body.

<u>GONIOMETRY</u> (Nichol 1989)

Goniometry is the objective measurement of joint motion or joint position.

<u>LIGAMENT</u> (Butterworths Medical Dictionary 2nd Ed).

A thickened band of white fibrous tissue which connects bones and forms the capsule of joints.

<u>ORTHOSIS</u> (International Standards Organisation).

An externally applied device to modify the structural or functional characteristics of the musculo-skeletal system.

<u>SCANNING PEDOBAROGRAPH</u>

Used to collect footprint-pressure data as the subject walks over a mat containing force-resisting sensors. Also called after manufacturers of proprietary systems (ie Musgrave, F-Scan or E-Med).

<u>TOMOGRAPHY</u> (Butterworths Medical Dictionary 2nd Ed)

Body-section radiography, in which the x-ray tube traverses a non-linear pathway.

CHAPTER ONE

INTRODUCTION

Coronal plane range of motion of the ankle joint complex is a commonly used clinical measure. Dysfunction, following injury or disease, and improved function following surgical or medical intervention can be assessed, and treatment or further treatment can be planned depending on the examiner's findings. The coronal plane range of motion of the ankle is directly associated with a subjects ability to walk or run and it is therefore important to be able to measure any loss of motion accurately (Whittle, 1996).

The aims of this study are sixfold.

1. To develop a simple yet reliable research tool which will allow accurate *in vivo* measurements to be taken of maximum passive range of movement at the ankle joint complex.

2. To examine the mean equilibrium position of the foot in relation to the lower limb.

3. To look for any difference in the total passive range of motion of the ankle joint complex occurring in the coronal plane when the same torque is applied around an axis deviated 16 degrees medially, and an axis which bisects the calcaneus and the second metatarsal.

4. To look for any diurnal variation in passive range of motion occurring at the ankle joint in the coronal plane.

5. To look for any correlation between the passive range of motion of the ankle joint complex in the coronal plane in those patients who present with localised non-traumatic lower limb pathology, and localised non-traumatic foot pathology.

6. To examine the published evidence that foot, knee and leg problems can be helped by controlling coronal plane motion of the ankle joint complex with foot orthoses.

The objectives of this study are:

1. To gain a better understanding of the kinematics of the ankle joint complex.
2. To contribute to that body of knowledge which is involved with clinical practice in the field of the foot and ankle.

Mann (1982) has described the talocrural joint as being externally rotated and tipped in a distal, lateral direction and this suggests that sagittal plane motion at the ankle is accompanied by transverse plane rotation of the tibia. The sub-talar joint has been described as having a well-defined joint axis in the sagittal plane which has a mean orientation of 42 degrees relative to the sole of the foot and a mean orientation of 16 degrees in the transverse plane medial to the long axis of the foot (Green and Carol (1984), Czernieki (1988). The transverse or mid-tarsal joint is formed by the calcaneocuboid joint laterally and the talonavicular joint medially. It has been stated that movement at this joint is a combination of inversion, adduction and plantarflexion and eversion, abduction and dorsiflexion (Green and Carol (1984)).

In vivo studies which have been carried out into normal coronal plane ranges of motion of the ankle joint complex quote widely differing values, ranging from 29 degrees (Allinger and Engsberg (1992)) to 73 degrees (Alexander *et al* (1982)). There has been little uniformity in the work carried out so far, and each published work has used different methodology to obtain results. Alexander *et al* (1982) utilised passive movement around an axis which lay 16 degrees in the transverse plane and 42 degrees in the sagittal plane without quantifying what torque was applied. Allinger and Engsberg (1992) utilised active, unquantified movement, and Ball and Johnson (1996) applied quantified torque around an axis which lay horizontal in the sagittal plane and bisected the foot in the transverse plane. Some investigators have included the use of goniometers (Inman (1976), James *et al* (1978)) and tomography (Bailey *et al* (1984)) in their examination of coronal plane motion, either at the talo-crural or sub-talar joint.

Two theories of normal ambulation are compared (Duchenne (1855), and Dananberg (1993)). The importance of contra-lateral limb swing is described in relation to ambulation on a hard, horizontal surface with particular attention being paid to the mean equilibrium position of the foot in relation to the lower leg in the frontal plane. Minor deviation from a horizontal foot position, assuming a leg position which is perpendicular to the ground, may have an adverse effect on the lower limb, pelvis or spine as the foot compensates to conform to the hard horizontal surface upon which western culture spends most of it s time.

The conservative treatment (by means of functional foot orthoses) of conditions which have been described as pathological by some and normal by others is examined in detail, together with existing evidence of efficacy. A case history is presented of how functional foot orthoses altered foot shape and function in a 52-year old female patient over a twenty-month period, and an explanation both of the design of these devices and means of objective evaluation is provided.

The orientations of the talocrural and subtalar joints (collectively known as the ankle joint complex) have been well described and agreed on by several authors (Mann, (1982), Green and Carol (1984), Czernieki (1988)). Coronal plane motion at the ankle joint complex has also been well described (Allinger and Engsberg (1992), Alexander *et al (* 1982), Ball and Johnson (1996), Inman (1972), James *et al* (1978), Bailey *et al* (1984)). Unfortunately the literature quotes five different ranges-of-motion at the ankle-joint-complex, and utilises a variety of research methods.

This study has focussed on the development of a simple research tool which will allow accurate measurement of passive range-of-motion of the ankle-joint-complex in the coronal plane. Once design and development of the rig was complete the following experiments were carried out:

1. Reliability. To establish reliability of the rig and measurement methods, ten measurements were carried out on one subject.

2. Repeatability. Four sets of measurements were carried out on eight subjects.

3. Axis of rotation orientation. Two axes were tested. one which bisected the foot from heel to toe, and one which was inclined medially by sixteen degrees.

4. Footplate, counterbalanced and non-counterbalanced. ten measurements were taken of the same subject with the footplate counterbalanced and not counterbalanced. When the axis of rotation was inclined medially it was found that a residual torque was applied to the footplate. This necessitated a counterbalance being fitted to the footplate.

5. Comparison of three different applied torques.

6. Measurement of passive coronal plane range-of-motion of the ankle-joint-complex in one hundred subjects.

A secondary aim of this study was to examine commonly accepted theories of foot function and normal ambulation, and how foot function may be affected by means of foot orthoses.

In order to evaluate the effects of diurnal variation, rig axis of motion position, and anatomical axis pitch The following hypotheses were examined:

Hypothesis 1. *A statistically significant mean diurnal variation occurs in the range of passive motion occurring at the ankle joint complex when 4Nm of torque is applied around an axis which deviates medially by 16 degrees in the transverse plane, when readings are taken at two-hour intervals, commencing at 7.00am and finishing at 9.00pm.*

Hypothesis 2. *The mean total passive range of motion available when a known torque is applied at the ankle joint complex is significantly different when the torque is applied to an axis which deviates 16 degrees medially in the transverse plane than when applied to an axis which bisects the foot.*

Hypothesis 3. *A statistically significant difference is present in the amount of inversion and eversion ocurring at the ankle joint complex in patients who present with localised, non-traumatic lower limb pathology, and localised, non-traumatic foot pathology.*

This study is primarily concerned with the static measurement of the talocrural and sub-talar joints combined, which make up the ankle joint complex.
It has been suggested that functional foot orthoses allow the sub-talar joint to function around its neutral position (Pratt (1995)) and to this end it is common podiatric practice to take range-of-motion measurements of the sub-talar joint (Cook *et al* (1988)). Given the widely differing ranges-of-motion of the healthy sub-talar joint

quoted in the literature, and the uncertainty about whether range-of-motion of the sub-talar joint or the ankle joint complex is being measured, it would seem that any clinical measurement of the sub-talar joint used as the basis for a prescription for foot orthoses could only be useful as a rough guide. Further, Kilmartin and Wallace (1994) point out that no single piece of research has proved the advantage of placing the foot in a supinated or neutral position, rather than a pronated position.

The results of this study, and specifically the mean equilibrium position of the foot, together with mean coronal plane ranges of motion available, will contribute to the body of knowledge regarding passive range of motion at the ankle joint complex. The equipment and methodology used to collect data demonstrate the need to combine sound biomechanical principles and accurate instrumentation with an understanding of ankle joint axis orientation and how this can affect coronal plane motion.

CHAPTER TWO

MAJOR JOINTS OF THE FOOT

The joints of the foot and ankle can be divided anatomically into three major functional units; the ankle joint (or talocrural joint), the subtalar joint, and the transverse tarsal joint (Czernieki (1988)). It has been stated that each joint is capable of simultaneous movement in each of the three cardinal body planes, that is, sagittal plane movement, coronal, or frontal plane movement, and transverse plane movement (Green and Carol (1984), Mann R. A (1982)).

2.1 The talocrural joint.

The Talocrural, or ankle joint (fig 2.1), is formed by the distal end of the tibia articulating with the superior surface of the talus. The tibial and fibular malleoli are positioned medial and lateral to the tibiotalar articulation, with the fibular malleoli positioned posterior to the tibial malleoli. The talocrural joint is externally rotated and tipped in a distal, lateral direction (Mann (1982)). Joint orientation can be defined by a line passing through the tips of the medial and lateral malleoli. Functionally this is important as an oblique joint orientation would mean that forces acting on coronal plane motion at the ankle, for example pronation or supination of the sub-talar joint, is accompanied by transverse plane rotation of the tibia. It has been suggested that this is the case. Experiments carried out *in vivo* (D'Amico and Rubin (1986), Yasuda and Sasaki (1987)) and *in vitro* (Hinterman *et al*, (1993)) provide some evidence that coronal plane motion at the foot can cause tibial rotation. Yasuda and Sasaki (1987), using a wedged board, load transducers and X-rays, were able to demonstrate how a laterally wedged foot could reduce loading on the medial compartment of the knee in patients with medial knee arthritis. All three studies were carried out on small subject numbers (D'Amaco and Rubin, n = 21, Hinterman *et al*, n = 14, and Yasuda and Sasaki, n = 10.

2.2 The subtalar joint.

The subtalar joint (fig 2.2) is formed by three facets, anterior, middle and posterior, on the under-surface of the talus which articulate with the upper surface of the calcaneus (Czernieki (1988), McMinn *et al* (1996)). The talar articulations have been described as functioning as a single joint with a well defined joint axis in the sagittal plane. This is said to have a mean orientation of 42 degrees relative to the sole of the foot, running in a posterior and distal direction between the dorsal aspect of the neck of the talus and the posteriolateral corner of the calcaneus (Manter (1941), Root *et al* (1966) and Green and Carol (1984)) (fig 2.3). In the transverse plane the axis is described as being positioned a mean of 16 degrees medial to the long axis of the foot (fig 2.4) (Manter (1941), Green and Carol (1984)).

2.3 The transverse tarsal joint.

The transverse, or mid- tarsal joint of the foot (fig 2.5) is formed by the calcaneocuboid joint laterally, and the talonavicular joint medially (figs 1 and 2). Mann (1982) suggested that movement at this joint is primarily in the plane of abduction/adduction, although Green and Carol (1984) stated that, because of axis orientation, movement at the calcaneocuboid joint is a combination of inversion, adduction and plantarflexion (supination), and eversion, abduction and dorsiflexion (pronation).

2.4 Major ankle-joint-complex ligaments.

The ligaments which help to support the ankle and sub-talar joints are:

<u>Medially.</u>

- The anterior tibio-navicular ligament.
- The calcaneo-tibial ligament.
- The posterior talo-tibial ligament.

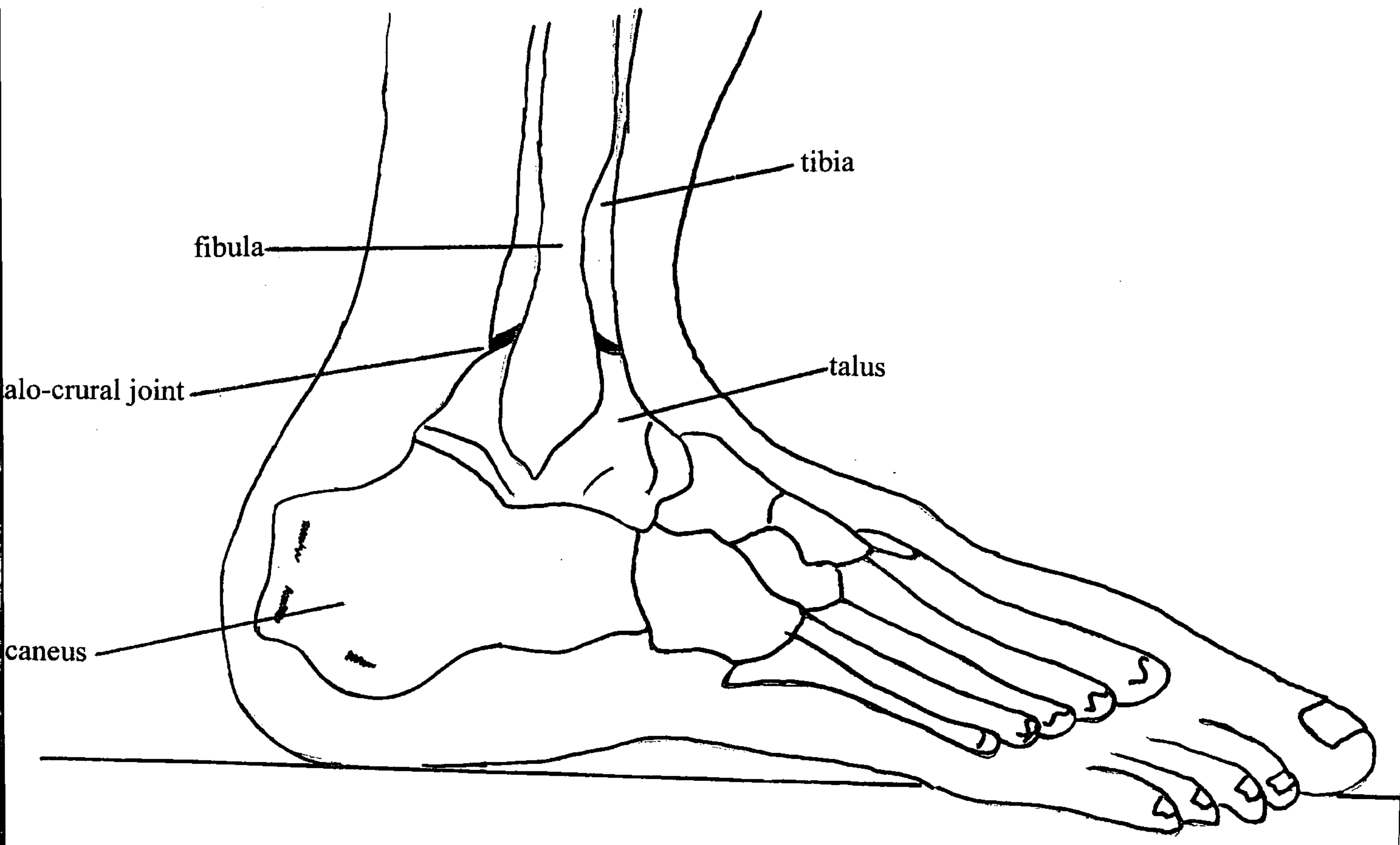


Fig 2.1. The talocrural joint.

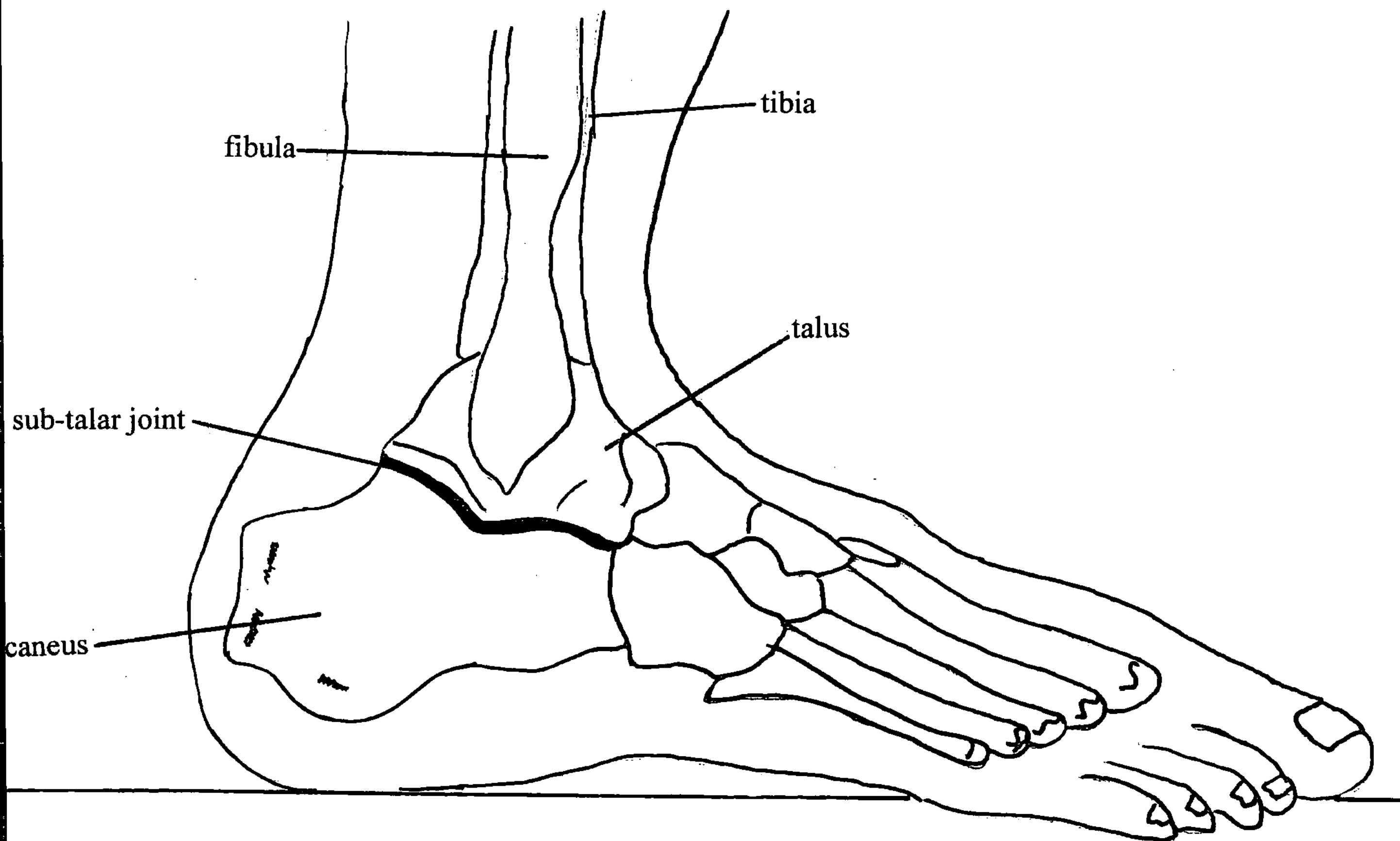


Fig 2.2. The sub-talar joint.

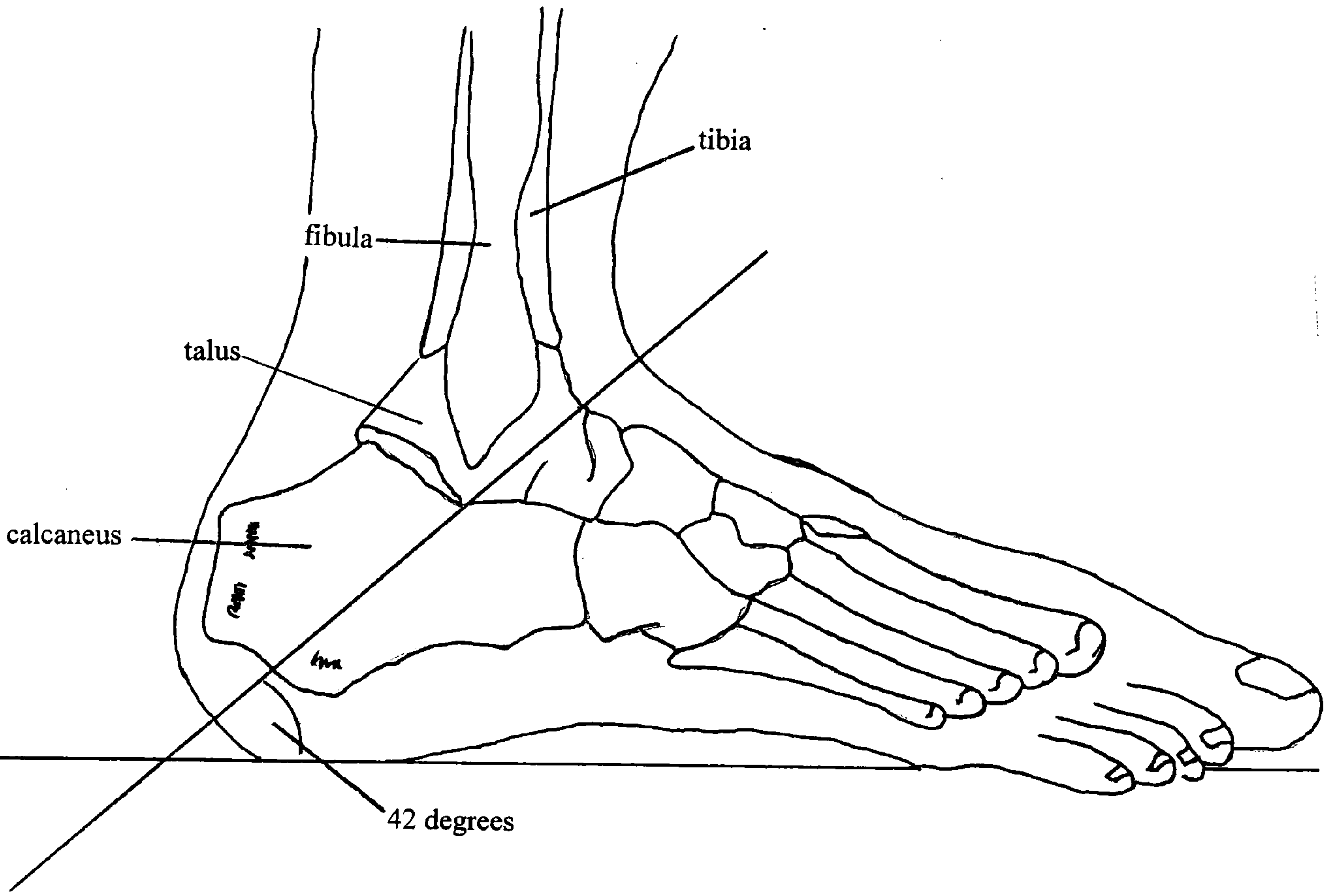


Fig 2.3. Subtalar joint axis (sagittal plane).

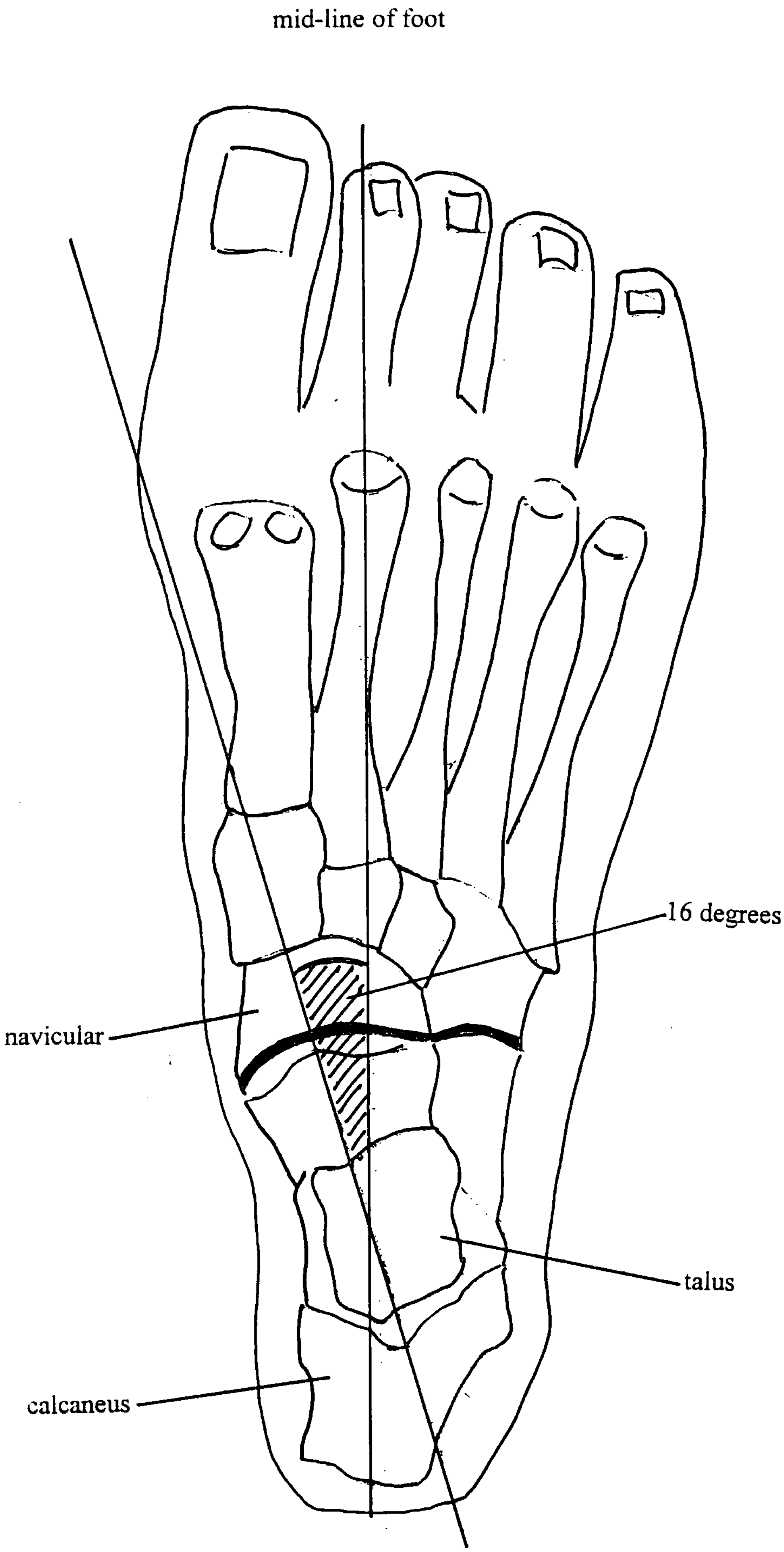


Fig 2.4. Subtalar joint axis (transverse plane).

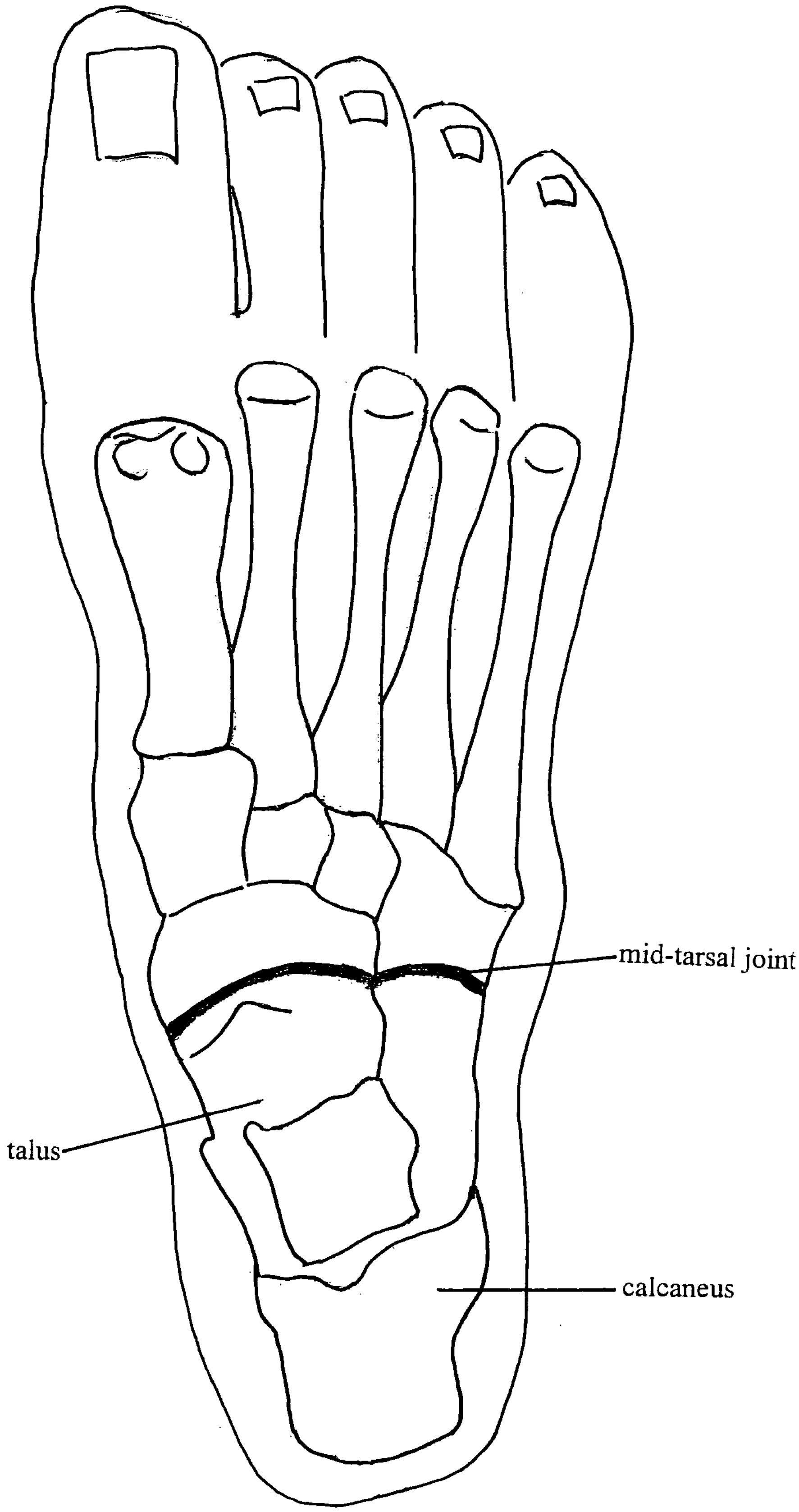


Fig 2.5. Transverse or midtarsal joint.

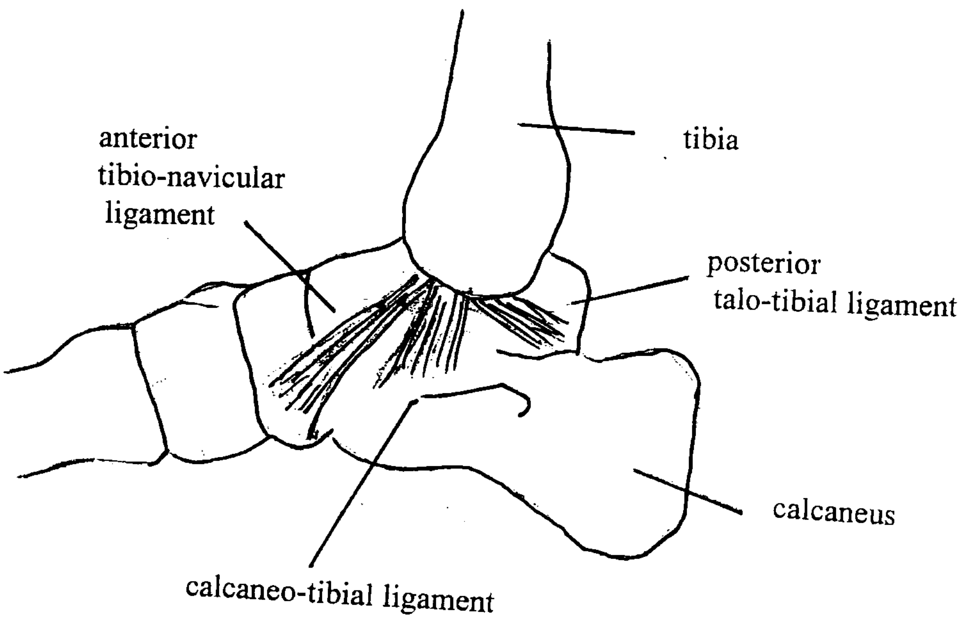


Fig 2.6. Medial ankle joint complex ligaments.

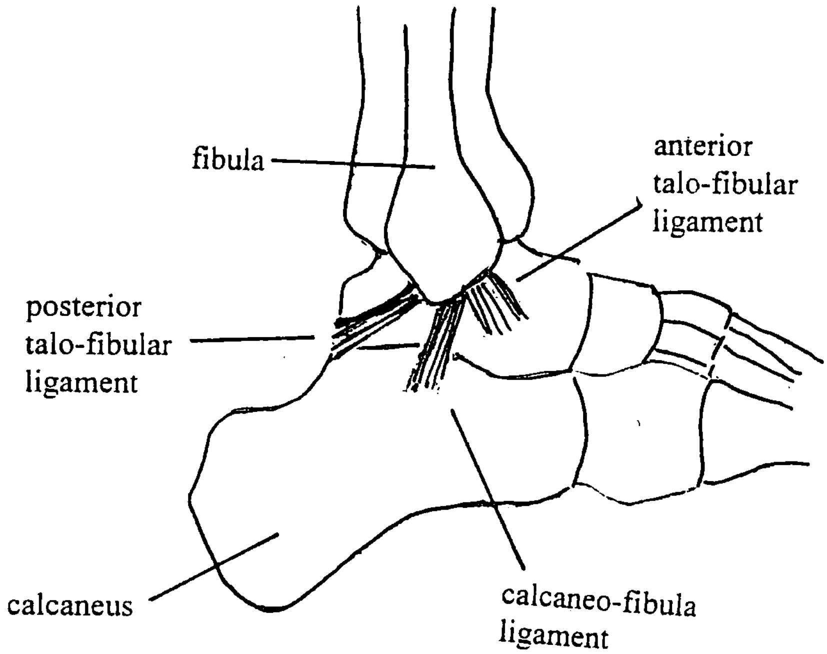


Fig 2.7. Lateral ankle joint complex ligaments.

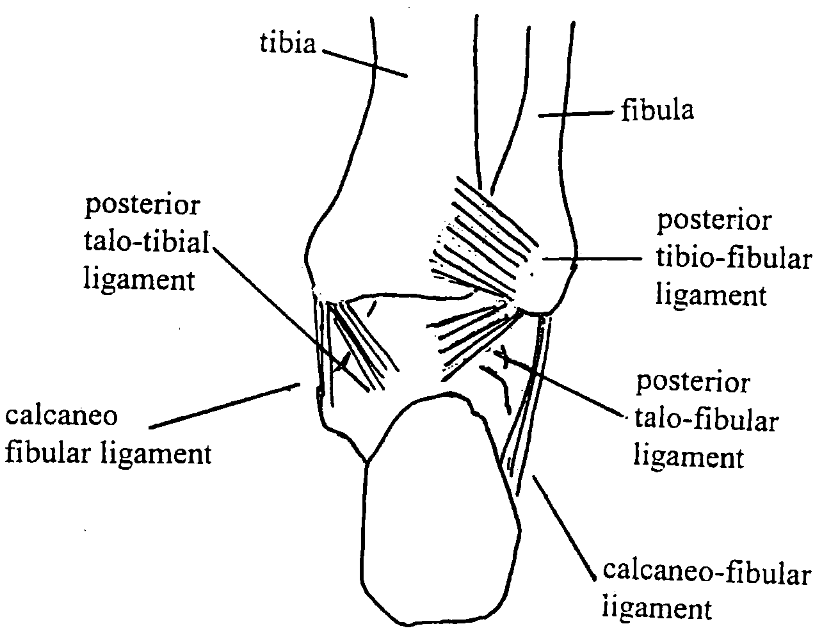


Fig 2.8. Posterior ankle joint complex ligaments.

Laterally.

- The anterior talo-fibular ligament.
- The calcaneo-fibular ligament.
- The posterior talo-fibular ligament.

The ligaments on the lateral side are short, being confined to the fibula, calcaneus and talus, wheras medially the anterior tibio-fibular ligament extends to the mid-foot (see figs 2.6, 2.7 and 2.8).

2.5 Sub-talar motion.

Hindfoot inversion and eversion are the parameters typically measured when subtalar joint motion is assessed, and most *in vivo* studies have relied on skin measurements, utilising the technique of marking a bisection of the lower third of the leg and calcaneus, and measuring calcaneal inversion/eversion from the angle formed between the heel and the leg as the calcaneus inverts/everts (Phillips *et al* (1985), Garbolosa *et al* (1994)).

Phillips *et al* presented an *in vivo* technique for assessing clinical range-of-motion in the sub-talar joint in the frontal, sagittal and transverse planes. This involved drawing lines on a bisection of the heel and lower third of a subject's leg. Part of this paper introduced a complicated formula for working out the axis of motion of the individual sub-talar joint. However Menz and Keenan (1997) was able to demonstrate that measurements taken from skin markings are liable to error, and the accuracy, and therefore effectiveness of any technique which uses skin markings to measure in degrees is open to question.

Some studies on range-of-motion of the sub-talar joint have been carried out *in vitro,* and these do suggest axes of motion, from which both planes of motion and the effects of ground reaction force (**grf**) on frontal plane motion of the calcaneus and tibia can be deduced with a reasonable degree of certainty.

Manter (1941), Hicks (1953) and Root *et al* (1966) all performed similar experiments using cadaver feet and pins or rods pushed into the talus to determine talar movement, and hypothesise sub-talar axes of motion. Findings were similar in the Manter and Root studies (table 2.1) and although Hicks did not quantitively define axis orientation he did conclude that the axis passed from the posteriolateral corner of the calcaneus to the superior medial aspect of the calcaneus. Root *et al* (1966) performed a refined version of Manter's 1941 experiment although he disputed Manter's hypothesis that sub-talar joint motion is screw-like in nature, as did Hicks. Twenty - two cadaver feet, with no obvious dysfunction of the tarsal or mid-tarsal areas, were dissected leaving only the ligaments intact. Three marking pins were inserted into the dorsum of the talus at random angles and the sub-talar joint was then moved from pronation (eversion, abduction and dorsiflexion) to supination (inversion, adduction and plantarflexion). By adjusting the length of each pin by trial and error a point was found at which each pin described an arc parallel to the arcs created by the other two pins and the arcs also remained on the same plane throughout the range of motion of the sub-talar joint. Root hypothesised that this represented a plane that was parallel to the plane of motion of the sub-talar joint, and that a perpendicular to this represented the axis of motion. Isman and Inman (1969) carried out a similar study using a larger cohort of 46 cadaver specimens, and their results were similar to previous researchers (table 2.1).

The importance of the often-quoted Root *et al* (1966) paper lies in the fact that it is detailed, and would permit replication of the original experiment. However it should be noted that in 22 subjects the researchers found wide variation in axis pitch (3 subjects exhibited high-pitched axes, 2 subjects exhibited low-pitched axes), and range-of-motion (5 subjects exhibited lax sub-talar joints, 7 subjects exhibited restricted motion sub-talar joints). This suggests wide variation in sub-talar normal range-of motion, borne out by the paper's published Coefficient of Variation of 20%

for axis deviation from the transverse plane and 13% for axis deviation from the sagittal plane.

Researcher	Year	Subjects	Transverse	Sagittal
Manter	1941	16	42 degrees	16 degrees
Root	1966	22	42 degrees	17 degrees
Inman	1969	46	46 degrees	23 degrees

Table 2.1. *In vitro* sub-talar axis orientation findings.

Imaging techniques have allowed joint motion studies to be observed *in vivo* and using a combination of mirrors, cinematography and radiology Viladot Jr, (1992) was able to demonstrate sub-talar joint motion from heel-strike to take-off in both the shod and unshod foot. Unfortunately the validity of this particular study was disadvantaged by the small number of subjects (n = 4), and the lack of any statistical tests.

2.6 The ankle joint complex.

The talocrural and subtalar joints, collectively known as the ankle joint complex, act together to provide a universal-joint type of linkage between the foot and the leg. This linkage allows simultaneous dorsiflexion and eversion, and plantarflexion and inversion of the foot (Alexander *et al (1982)),* as well as converting foot eversion and inversion into internal and external tibial rotation (Hinterman *et al* (1993)).

In an *in vitro* study, Hinterman *et al* (1993), using a lower-leg holding rig with 6 degrees of freedom, were able to induce significant internal tibial rotation by everting the calcaneus, but were unable to induce calcaneal inversion by internally rotating the connecting tibia. They found that vertical loading of the tibia and foot flexion position had a major influence on movement transfer. Specifically, foot plantarflexion rotated the tibia externally, while foot dorsiflexion rotated the foot internally. Axial loading of the tibia (from 0 N to 600 N) produced mild internal rotation of the tibia. It may be assumed from these findings that the foot may have a significant effect on transverse plane motion in the lower leg (and presumably the upper leg, pelvis and spine).

2.7 Axis orientation relevance.

In vivo research on sub-talar joint motion carried out by Alexander *et al* (1982) utilised a rig which allowed passive movement around an axis which lay 42 degrees in the sagittal plane and 16 degrees in the transverse plane. This study (n = 140) found a mean total range of motion of 73.8 degrees. Although this is higher than the results of other studies into ankle joint coronal plane range-of-motion (Bailey *et al*, (1984), Allinger and Engsberg (1992), Ball and Johnson (1996)) it should be viewed with caution since the applied torque was not quantified. Alexander *et al* (1982) were happy that they could separate sub-talar joint motion from talocrural joint motion, but this is at variance with later findings from other investigators (Hinterman *et al* (1993).

Czernieki (1988) stated that it is difficult to measure subtalar joint motion, either clinically or in the gait laboratory because the motion occurs in a number of planes. Bailey *et al* (1984) were able to study the neutral position of the subtalar joint in 15 subjects using a relatively sophisticated imaging technique. They also measured total passive range of motion of the subtalar joints by maximally inverting and everting the calcaneus. Unfortunately the results of this study were hampered by a small number of subjects, also, like the Alexander study, they did not quantify the amount of torque used to invert and evert the calcaneus. They found a mean subtalar range of motion of 25 degrees, and it is possible that the high ranges of motion found by Alexander *et al* (1982) were not just of the subtalar joint, but also included movement at the talocrural joint.

Passive movement of the ankle joint complex using an axis tipped 16 degrees medially in the transverse plane, and inclined 42 degrees in the sagittal plane in the Alexander *et al* study (1982) produced a total mean range of motion of 73.8 degrees.

This may be higher than other published studies simply because a higher torque was used to move the sub-talar joint. It is also possible however, that by utilising a sub-talar joint axis orientation as described by Manter (1941), Root (1966), Green and Carol (1984), Alexander *et al* were able to produce more sub-talar joint movement for the same, or less, torque as other researchers.

CHAPTER THREE

NORMAL FOOT FUNCTION

The healthy foot is said to be capable of two specific functions during gait (James *et al* (1978)).

- It acts as a shock-absorber, and adapts to irregularities of the ground during the initial contact phase of gait.
- It converts to act as a lever for propulsion during the latter part of the contact phase of gait.

Viladot Jr (1992) was able to demonstrate that at the moment of heel strike the calcaneus is in slight varus, which alters to valgus as weight is placed on the heel. Eversion occurs at the ankle joint complex, allows the mid-tarsal joint to slacken, and this allows for conformability between the foot and the ground as loading of the foot progressively increases. Maximum valgus is reached at mid-stance, after which, as the heel lifts off the ground and the calcaneus starts to move into varus, the mid-tarsal joint tightens and the forefoot becomes a lever capable of propulsion.

3.1 Foot function and ambulation.

The mechanics of normal gait and foot function are not fully understood, although sagittal plane motion of the support limb during gait has been described by several authors (Craik and Oatis (1995). Dananberg (1993)) has suggested that the swing phase (performed by the contralateral limb) is far more important than was previously thought and can be considered to be the "pull phase" of a step, necessitating only that the hip and knee of the support leg are extended during toe-off . This hypothesis was originally propounded by Wilhelm and Eduard Weber in Leipzig in 1836. It contrasts with another widely accepted theory that the support leg (particularly the gastrocnemius and soleus) is responsible for actively plantarflexing the ankle for heel-off/toe-off. (Winter *et al* (1995)). However, this is also based on an early hypothesis by Amand Duchenne (1855) whose work showed that subjects with paralysis of the lower limb circumvented the involved extremity to clear the limb during the swing phase of gait. Duchenne argued that if gravity alone were responsible for ambulation no compensation would be necessary (Johanson (1994)).

The gait cycle.

Defined as the time interval between two successive occurences of one of the repetitive events of walking (Whittle (1996)) the gait cycle can be divided into two parts; the stance phase, and the swing phase. These can further be divided into their respective components.

Stance phase.

Loading response (heel-strike).

Mid-stance.

Terminal stance.

Pre-swing.

Swing phase.

Initial swing.

Mid-swing.

Terminal swing.

In normal walking, as one foot hits the ground (loading response/heelstrike) the other foot will still be on the ground. This is known as double support phase. As loading response progresses into midstance, the other foot will have left the ground and is now in initial swing phase. The stance phase leg progresses to pre-swing and the other foot is now on the ground at loading response/heelstrike.

Hip motion.

The hip flexes and extends once during the gait cycle. Maximum flexion, normally 30%, is reached around the middle of swing phase (Whittle (1996)).

Knee motion.

The knee extends at the end of swing phase, and starts to flex again just after initial contact.

The ankle and foot.

The ankle joint (talocrural joint) is dorsiflexed at heelstrike, moving into plantarflexion following initial contact. The ankle moves into dorsiflexion during swing phase ready for the next heelstrike.

At heelstrike to heel is usually inverted, and because of this most people show a wear pattern on the outside of the heel. (Whittle (1996)).

3.2 The importance of contralateral limb swing.

Dananberg's theory, (Dananberg (1993)) which is a refinement of the Weber brothers hypothesis, suggests that momentum induced by the swing limb pulls the centre of mass of the body forward. For this to happen the weight of the body must be directly over the stance foot.The swing movement of the contralateral limb moves the contralateral hip forward in relation to the stance hip, rotating the stance leg externally which inverts the stance foot. This action is complemented by the windlass action of the plantar aponeurosis described by Hicks (1953) which states that as the great toe is dorsiflexed, the distal attachment of the plantar aponeurosis is tightened, and the foot is inverted. The Dananberg theory oversimplifies the gait cycle, without taking into account major joint moments (Paul (1967)) or centre-of-mass shift due to trunk inclination. His observations are also dependent on the subject ambulating on unyeilding, horizontal surfaces such as pavement or concrete. Once the surface becomes undulating or soft, swing limb motion and great toe dorsiflexion will be affected, and both muscle function and gait will adapt accordingly.

3.3 The knee joint.

The knee is composed of two joints; the patellofemoral joint, made up of the medial and lateral condyles of the femur arcticulating with the patella, and the tibiofemoral joint, made up of the distal portions of the medial and lateral condyles of the patella acticulating with the condyles of the tibia (McMinn *et al* (1996)). In the frontal or coronal plane the knee joint exhibits a valgus angle of approximately 6 degrees. It is important to understand that although motion in the tibiofemoral joint takes place in all three planes, albeit predominantly in the sagittal plane, it is influenced in the transverse plane by the position of the joint in the sagittal plane, specifically extension. This is because when the knee is extended the joint cannot rotate due to the femoral and tibial condyles interlocking. The range of transverse plane motion increases as the joint is flexed. (Nordin and Frankel (1989)).

During normal walking the gait sequence can be divided into two distinct periods; stance time, when the bodyweight is on the limb, and swing time, when the limb swings clear of the ground (Whittle (1996)). Because motion at the knee joint occurs mainly in the sagittal plane (Nordin and Frankel (1989)) it is relatively straightforward to describe knee joint involvement during normal gait. In stance time, as the heel hits the ground the knee which was extended, flexes as the limb is loaded, extends as the limb pushes off, and flexes again during swing phase(Whittle (1996)).

3.4 The Q Angle.

An *in vivo* study carried out by Olerud and Berg (1984) on 34 healthy volunteers using three separate measurement methods concluded that the **Q**-angle (the angle between the rectus femoris muscle and the patellar tendon by which the valgus angle of the knee can be measured using soft tissue landmarks) increased as the foot inwardly rotated, and decreased as the foot outwardly rotated (fig 3.2). They suggested that in order to measure the **Q**-angle accurately, the foot position should be standardised, giving weight to the argument that foot position can indeed affect the knee.

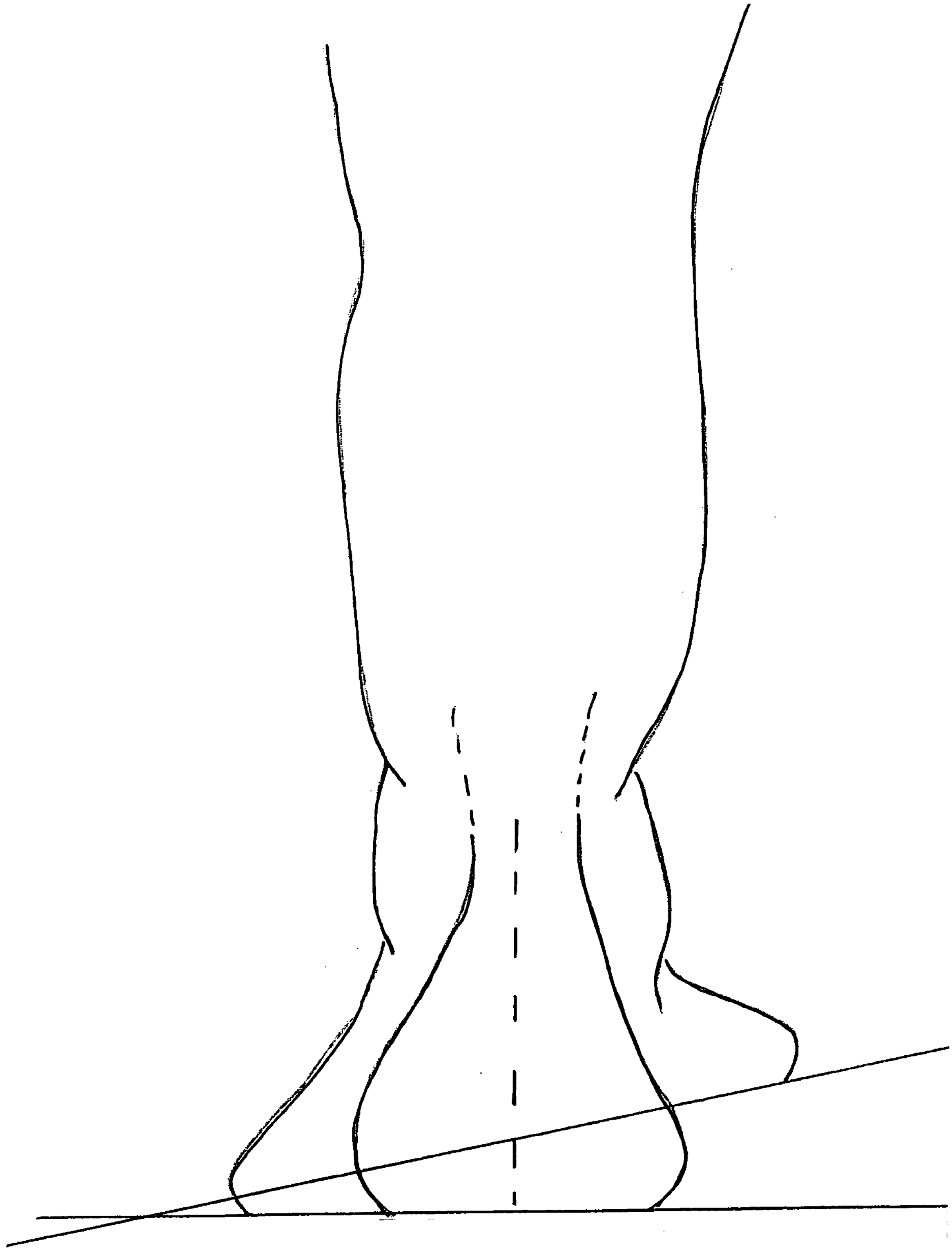


Fig 3.2. Forefoot Invertus.

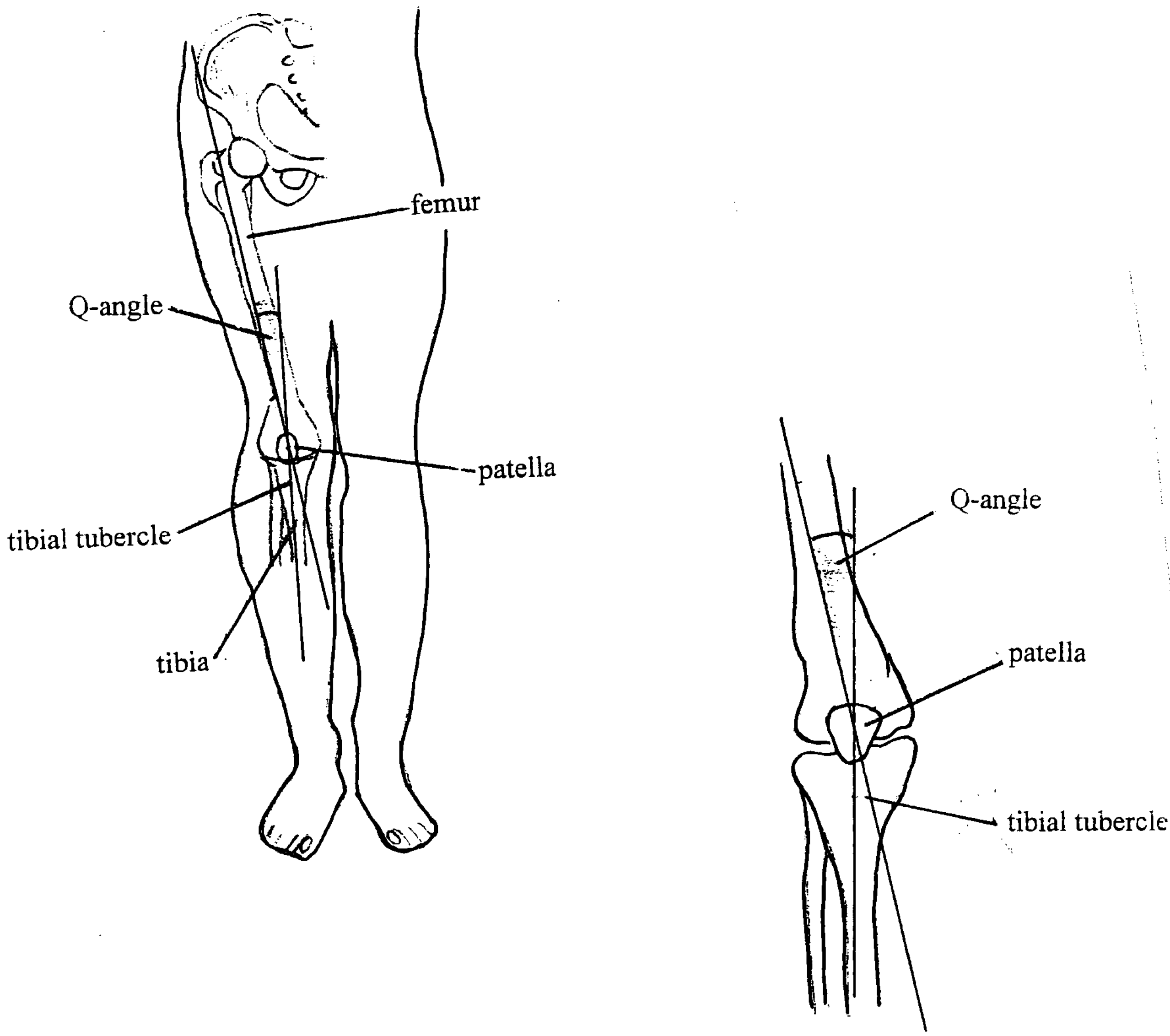


Fig 3.2. The Q-Angle.

3.5 Foot function and lower limb pathology.

There are many theories surrounding the effects of foot function on other parts of the body. Eng and Pierrynowski (1993) carried out a study which suggested that by controlling foot motion patellofemoral pain syndrome may be helped. This research involved prescribing an exercise programme for 20 adolescent female patients with patellofemoral pain syndrome, of whom ten were also prescribed soft foot orthoses. The results demonstrated a significant decrease in the level of pain for the whole group,and a significantly greater decrease in pain for the group wearing orthoses. Subjective pain reduction assessment methods were employed for this study and although interesting it offers no real evidence that patellofemoral pain can be helped by altering foot function.

An *in vitro* study by Hinterman *et al* (1993) showed how tibial rotation could be influenced by calcaneal eversion, Hefzy *et al* (1992) found that tibial rotations caused stastistically significant differences in patellar tilt, patellar rotation and patellar medial-lateral shift *in vitro*, while Nawoczenski *et al* (1995) found that foot orthoses were able to decrease internal tibial rotation *in vivo* significantly. It has also been demonstrated how foot function can affect knee joint kinematics in the arthritic knee. Yasuda and Sasaki (1987), examined ten women with medial compartment arthritis of the knee. Using a wedged board, load transducers and X-rays, they were able to demonstrate how a lateral tilt in the weightbearing foot decreased excessive loading in the medial compartment of the knee. It is assumed, although not stated in the paper, that high medial compartment loading was an etiological factor in the knee pathology.

The literature is divided as to what is a foot condition requiring treatment, and what is normal. In paediatrics it has been stated that minor malalignments and deformities of the feet can lead to genu-varum and valgum-related degeneration of the knee, shin-splints, medial knee injuries, chondromalacia patellae and piriformis sciatica, and that these foot conditions should be treated (Pratt and Sanner (1996)), while other authorities regard paediatric minor foot anomilies as normal, requiring no treatment (Walker (1994)).

Two podiatric conditions, forefoot varus (invertus) (fig 3.1) and forefoot valgus were amongst those described by Pratt (1995), along with treatment rationale and methods, and yet Garbolosa *et al* (1994) were able to show, in a study involving 120 healthy subjects (234 feet), that 83% of the subjects exhibited forefoot invertus (mean 8 degrees) suggesting that forefoot invertus (also called forefoot varus and forefoot supinatus), where the forefoot is inverted in relation to the hindfoot when the subtalar joint is placed in neutral, is simply a variation of normal. Some authorities have also stated that the normal foot has no effect on forces transmitted through the knee joint (Kettlekamp and Chao (1972)), and this view has been reiterated by others more recently, notably Goldberg *et al* (1989), Bindleglass *et al* (1993), and Davidson (1993).

A review of the literature suggests that the dichotomy of what constitutes a condition requiring treatment is not confined to feet, and their effects on legs and knees. Rosenbaum *et al* (1997), in their study on the biomechanical consequences of ligament injuries and surgical reconstructions, stated the widely held medical view that excessive ligamentous laxity of the ankle joints is considered a pre-arthritic condition, and although excessive ligamentous laxity is recognised as a medical condition (Kirk (1967)) there has been little valid research on what constitutes excessive laxity in the ankle. Mean ROM of inversion in the healthy ankle is variously quoted in the literature as 35 degrees (McRae (1990)), 18 degrees (Allinger and Engsberg (1992)), 32 degrees (Ball and Johnson (1996)), and 42 degrees (Alexander *et al* (1982)). Each author employed different methods (McRae did not state where his data came from) and it can be assumed that axis position, applied torque values, and variable experimental rigour have had an effect on results.

CHAPTER FOUR

FOOT ORTHOSES, CLAIMS AND EFFECTIVENESS

The International Standards Organisation's (ISO) definition of an orthosis is: *An externally applied device to modify the structural or functional characteristics of the musculo-skeletal system* (ISO 1989). A foot orthosis then, can be considered to be one of any of the following; modified footwear, padding and strapping, simple insoles and rigid and semi-rigid insoles produced on casts of the feet.

The use of prescription foot orthoses to treat foot and lower limb conditions came to prominence in the late 1960's, following work carried out by a Californian podiatrist, Merton Root, in the early 50's and 60's. Their design and explanations of how they worked was based largely on trial and error by Root and colleagues (Pratt (1995)), complemented by earlier research into foot and lower limb function by Manter (1941) and Hicks (1953).

Foot orthoses have had extensive claims made for their effectiveness (Dananberg, (1993), Eng and Pierrynowski (1993), Pratt (1995), Pratt and Sanner (1996), Nawoczenski *et al (*1995)) and this chapter describes how researchers have been unable to show, by scientific methodology, how - or indeed if - functional foot orthoses work (Kilmartin and Wallace (1994)). Garbolosa *et al* (1994), in a study involving 234 asymptomatic feet, were able to demonstrate that one of the more common foot "conditions" which some authorities suggest should be treated with foot orthoses, was in fact present in 83% of their subjects. This example highlights a major problem in the design and prescribing of foot orthoses, and may answer in part why researchers have been unable to show how or if prescription foot orthoses work. Research into foot and lower limb function carried out later than the 1970's would seem to have been largely ignored by those who design and prescribe foot orthoses.

A case study has been presented which uses a computer footprint system to show how a tangible improvement in foot function has been acheived over a twenty-month period using foot orthoses, the design of which, although simple, has drawn on relatively recent research in this field (Cornwall and McPoil (1992), Dananberg (1993), Garbolosa *et al (*1994)).

4.1 Functional foot orthoses.

Functional foot orthoses are made from a plaster cast of the foot with the sub-talar joint held in neutral (Pratt (1995)). The orthoses are balanced to horizontal, at the rearfoot or forefoot or both, on the shell of the device which can be made from various materials, from polypropylene to carbon-fibre (Langer Laboratories UK) (fig 4.1). Different authorities suggest different methods of fabrication (Anthony (1991), Philps (1991), Dananberg, personal communication) and no one method of orthosis construction has been proved to be more effective than the others.

Podiatrists and other health-professionals such as Root *et al* (1966), Landry and Zebas (1985), Yasuda and Sasaki (1987), Eng and Pierrynowski (1993) and Moraros and Hodge (1993)), working in the field of clinical gait analysis have long assumed a connection between foot function and certain types of lower limb pathology. Howard Dananberg (1993) described how a functional inability of the 1st metatarsal joint could cause and perpetuate postural ailments such as lower back pain, while Buchbinder *et al* (1979) examined the relationship between abnormal (excessive) pronation of the foot and chondromalacia of the patella in long-distance runners, illustrating how prolonged sub-talar joint pronation, beyond 25% of stance phase, may be accompanied by prolonged internal leg rotation, causing a malalignment of the patella and an internal rotation of the femur, thus creating an abnormal quadriceps pull on the patella.

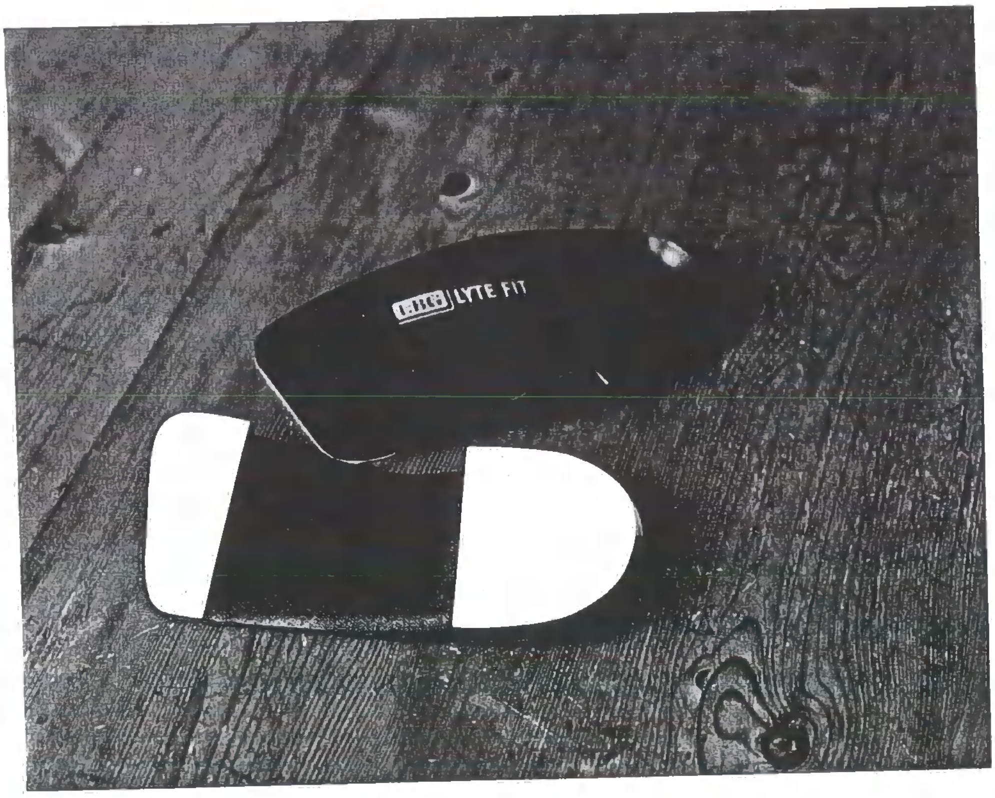


Fig 4.1. Functional foot orthoses.

4.2 Functional foot orthoses evaluation.

There are several ways to evaluate foot orthosis performance.

Kinematics.

Video recording can be used to compare gait with and without orthoses.

Measurement of ground reaction forces.

This is done with a force platform (forceplate), an instrument which can measure the total force applied to the ground by the foot (Whittle (1996)).

Foot pressure measurement.

This may also be measured with certain types of forceplate which can quantify plantar pressure.

Cornwall and McPoil (1992) carried out a single-subject study in which dynamic forefoot vertical forces were measured and compared. Measurements were taken using a commercially available in-shoe system (EMED) while the subject was shod, shod and wearing a semi-rigid foot orthosis without a varus wedge, and shod and wearing a semi-rigid foot orthosis with a varus wedge. The results showed that both orthoses significantly reduced the forefoot force-time integral, a value which allows measurement of the area under the force-time curve. Additionally it was found that the orthoses increased the total forefoot area contacting the ground when compared to the shoe only measurements, but no significant difference was found in the measurements when the subject wore the orthoses with and without the varus wedge. The authors point out that the findings of any single subject design should be viewed with some degree of caution, but it is interesting that both orthoses had an often clinically desired effect, that of altering forefoot loading, especially so since most foot orthoses are traditionally prescribed with a rearfoot varus post (Pratt and Sanner (1996).

Claims for the effectiveness of orthotic foot control in in-toe and out-toe gait in paediatrics, improved knee function in cases of patellofemoral pain, and the reduction of heel and metatarsal pain and plantar callousities have been made by several authors

(Pratt and Sanner (1996), Nawoczenski *et al (*1995), Eng and Pierrynowski (1993), Moraros and Hodge (1993)). Pratt and Sanner (1996) outlined a rationale for the provision of foot orthoses for paediatric patients, stating criteria for normal gait, and deviations from those criteria which may need treatment with foot orthoses. Nawoczenski *et al* (1995) stated that foot orthoses have been used successfully in the treatment of musculoskeletal symptoms associated with structural variations of the foot. They carried out a kinematic analysis of the effects of foot orthoses on tibial rotations and found a mean reduction of 2 degrees in tibial internal rotation when orthoses were worn. The study did not measure the effects of subject footwear which was specially adapted, and it is therefore impossible to say that this reduction in tibial rotation was caused by orthoses alone. Buchbinder *et al* (1979) described how patellofemoral pain could be alleviated by the use of foot orthoses, and presented a single-case study, but without any objective data to back up claims of treatment effectiveness. Moraros and Hodge carried out a patient satisfaction survey on 465 patients and orthoses effectiveness was reported as follows: Completely resolved presenting condition, 139. Partially resolved presenting condition, 272. Unresolved presenting condition, 54. Again no objective data were presented to back up these figures. It is also interesting to note that a radiographic study of the feet of ten children with Pes Planus, carried out by Penneau *et al* (1982) found no significant change in the shape of the feet with orthoses.

Although anecdotal evidence is abundant that orthoses do work, no reproducible experiments have been carried out and no scientific evidence has been produced to date to demonstrate effectiveness of foot orthoses. It is interesting that two of the podiatric texts which provide guidelines for the prescribing and manufacture of foot orthoses not only present divergent approaches, but imply that an incorrectly prescribed device (ie not using their specific approach) may cause serious damage to the wearer (Philps (1991), Anthony (1991)). Additionally it must be of concern to anyone fitting prescription foot orthoses that a recent study found that measuring devices commonly used to measure calcaneal inclination angles so that an accurate prescription can be written, have poor inter and intra-tester reliability (Menz and Keenan (1997)).

4.3 Single case study.

Dynamic computer-generated footprints are presented of a fifty two year-old woman with no history of systemic disease or long-term medication of any kind before orthoses were fitted, and twenty months after. Clinical examination of the lower limb mechanics of this patient revealed a bi-lateral foot mechanical anomaly - forefoot valgus. This is a coronal plane anomaly, a fixed osseous deformity in which the forefoot plane is everted relative to the calcaneal bisector with the foot in its neutral position (Pratt (1995)). This patient attended a chiropodist regularly for removal of plantar callousities. Recently the visits had become more frequent so that by the time she had her orthoses fitted she was having chiropody treatment every four weeks, but in discomfort after two weeks.

A functional foot orthosis is normally used to correct any compensatory changes in the leg or foot if it does not meet with the ideal of the plane of the forefoot lying at 90 degrees to a bisector of the calcaneus. This may be done with corrective posting at the heel, or heel and forefoot (Pratt (1995)). However, data from the literature search and this study suggested that may be normal for the forefoot not to be in a plane 90 degrees to a bisector of the calcaneus (Garbolosa *et al* (1994)). Cornwall and McPoil's single subject study (1992) indicated that a corrective rearfoot post may not be necessary, and intelligent use of this data allowed a much simplified foot orthosis to be designed and used in this single case study.

To allow quantitative before-and-after comparison the patient had a scanning pedobarogram (Musgrave Systems Ltd) taken before treatment. Footprint scans are not part of normal pre-treatment protocol, largely because of time or financial constraints, although it is obviously advantageous to both patient and clinician to be able to measure outcomes objectively. The footprint data, was collected dynamically (that is, with the subject walking) and unshod. The Musgrave System used to collect the data consists of one or two footplates (depending on the setup used) each containing 2048 sensors which are electronically scanned with a speed of 113,777 sensors/sec. The patient walks across the footplates, the footstep is recorded and the resulting load read into the computer. Data presentation allows detailed analysis for pre and post-treatment comparison.

Observable improvements to the left foot include reduced loading on the first and second metatarsal heads, increased loading on the lateral border of the foot and increased toe activity. Improvements to the right foot include reduced loading at the first metatarsal head. It is not unreasonable to assume that the foot orthoses have been responsible for the improvement to foot function, since footwear and exercise habits were not changed and there is no evidence that adult foot function will improve spontaneously. This is not meant to imply that all foot orthoses work, simply that foot orthoses were of demonstrable benefit in this case.

The key points of simplified orthosis design were:

- No correction at the heel (heel posting).

- Mild correction at the forefoot.

Anecdotal evidence, one-off case histories and a paucity of quatifiable data have meant that the way in which functional foot orthoses work is poorly understood. Methodology has not been uniform in the published studies which purport to demonstrate effectiveness of rigid and semi-rigid foot orthoses, and currently there are no scientifically acceptable data which show conclusively what effect, if any, foot function altered by foot orthoses has on the foot, ankle, leg and knee joint during ambulation.

CHAPTER FIVE

DEVELOPMENT OF THE MEASUREMENT RIG

5.1. Rationale for rig design.

The purpose of the rig was to allow the researcher to accurately measure inversion, eversion, dorsiflexion, plantarflexion and adduction and abduction in a number of subjects. It was necessary for measurements to be repeatable and reproducible, and it was felt that it would be useful for the rig to be portable for ease of data collection. This meant designing a strong rig which would be of a size which could be easily moved from location to location. The rig design is purely mechanical, obviating the need for electronic measuring equipment or electricity.

The prototype rig.

The prototype rig was adapted from a design published by Allinger and Engsberg (1992). This design featured a vertical cage to hold the lower leg in position, and a large foot carriage assembly to obtain measurements. The prototype rig for this study featured a similar method for holding the leg securely while measurements were taken. This utilised a vertical adjustable clamp to secure the knee, a metal v-shaped retaining bar which fitted adjacent to the tibial tubercle, and two adjustable clamps to secure the ankle. A metal heel-cup was fixed to each footplate, and fabric foot-straps secured with plastic buckles held the heel and forefoot.

A series of tests with the prototype rig (n= 15) showed that in all cases subjects were uncomfortable if the leg clamps were tight enough to hold the leg securely. An early modification to the design involved removing the vertical clamp and replacing with a second pair of adjustable, horizontal clamps which held the leg below the knee. These, too were found to be uncomfortable, and the design was revised, replacing the knee clamps with adjustable large foam pads, removing the metal retaining bar, and altering the design and position of the ankle retaining clamps, which were moved up the frame to 170mm from the footplate, and increased in size.

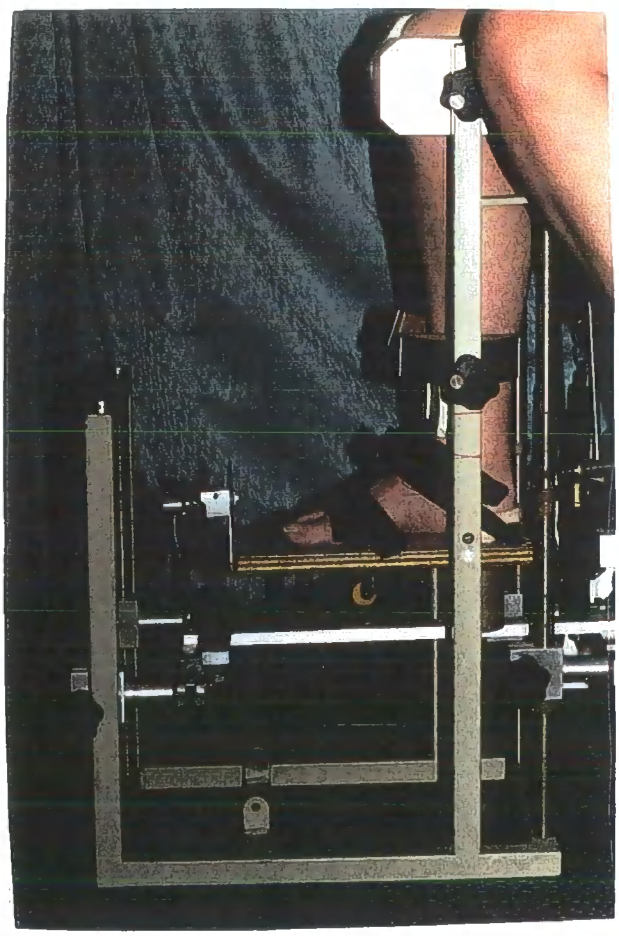


Fig 5.1. Rig and footplate assembly.

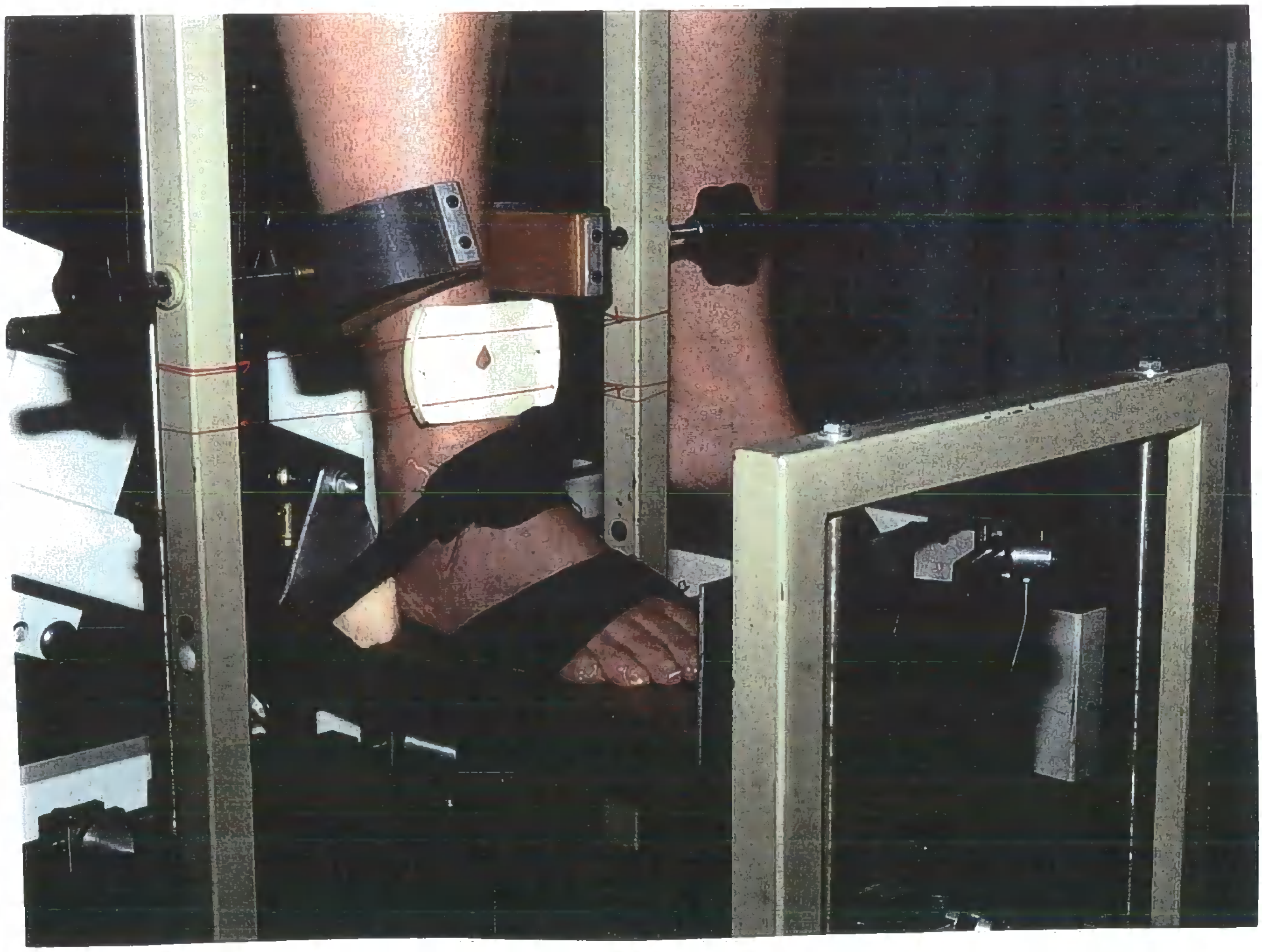


Fig 5.2. Footplate and plastic leg-movement shield.

5.2 The rig.

To allow accurate data collection, a purpose-built rig was fabricated (fig 5.1). This allowed for separate measurement of passive range of motion (ROM) of add/abduction, dorsi/plantarflexion, and in/eversion of the ankle joint complex. The rig was built around an L-shaped frame into which three footplates (one for each plane of motion) could be fitted. To obtain each measurement a known torque, 4Nm, was applied to the footplate.

5.2.1 The Frame.

The frame was constructed of 25mm mild steel box tubing, of dimensions 75mm high, 30mm wide and 40mm deep. The frame had tracks at the front and rear which held U-supports for the footplate lugs. These allowed upwards/downwards adjustment of the footplates to allow a comfortable fit between the foot and footplate, and provided support for two 10mm steel bars which supported an aluminium bar into which were attached the in/eversion footplate and the ab/adduction footplate.
Two pairs of adjustable clamps ensured that the leg was held securely during measurements, and any leg movement was noted against a 10mm window cut into a 7cm diameter plastic shield fixed to the frame and positioned in the middle of the subject's leg 15cm from the footplate.

5.2.2 Ab/adduction footplate.

This footplate had a centrally-placed pivot located at the bisection of the mid-line of the foot by the sub-talar joint axis. The front half of the footplate was faced with perspex and marked in 5 degree arcs. A pointer between the bottom (plywood) layer and upper (perspex) layer, allowed movement in ab/adduction to be read. The footplate was capable of measuring 60 degrees of adduction and 60 degrees of abduction.

5.2.3 Dorsi/plantarflexion footplate.

This footplate pivoted in the frontal plane from two lugs which were positioned at the bisection of the mid-line of the foot by the sub-talar joint axis. The front of the footplate was secured on an adjustable rail which was marked in 5 degree sections. Before each measurement was taken, the footplate was aligned by using a spirit-level to ensure that the footplate was at 90 degrees to the rig frame. The footplate was capable of measuring 50 degrees of plantarflexion and 25 degrees of dorsiflexion.

5.2.4 In/eversion footplate.

This footplate was connected to a ball-joint at the back, and a spindle at the front. Two axes were used to obtain measurements. The first axis closely followed the orientation of the sub-talar joint axis in the transverse plane as described by Green and Carol (1984), and was angled at 16 degrees from the bisection of the mid-line of the foot. The second axis followed a bisection of the foot. A similar, recent study carried out on 100 healthy subjects of both sexes by Ball and Johnson (1996) showed that by utilising an axis which approximated to the anatomical axis of the foot, and applying 10 Nm of torque they were able to record inversion values of 32 degrees, eversion values of 20 degrees and a total range of motion of 53 degrees. Since one of the footplate axes in this study allowed more inversion and eversion for less applied torque, a decision was taken to allow the footplate to measure 90 degrees of inversion and 50 degrees of eversion.

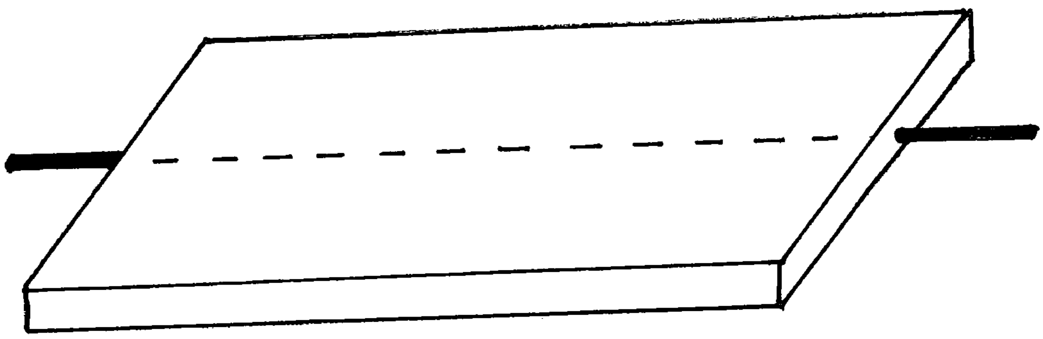
Initially this study was designed to investigate ankle joint complex passive range-of-motion in each of the cardinal body planes. It became apparent that measurement of coronal plane motion (inversion and eversion) of one large cohort would be more useful than measurement of motion in each body plane of smaller cohorts for the following reasons:

(1) Larger cohort numbers give a better chance of normal or near-normal distribution.

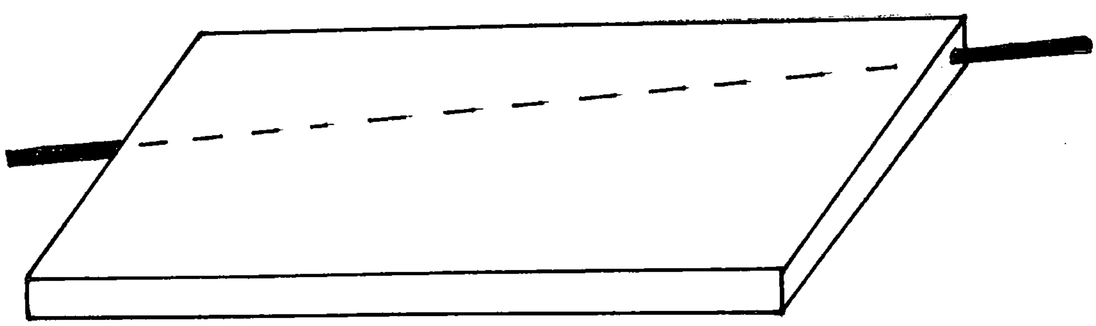
(2) Inversion and eversion measurements at the ankle joint complex have been the subject of previous publications (Alexander (1982), Bailey (1984), Allinger and

Engsberg (1993), and Ball and Johnson (1996)) and therefore there is already data available to compare the results with.

A decision was taken to confine the study to the examination of inversion and eversion at the ankle joint complex, utilising passive movement, a torque of 4Nm, and an axis which followed that described by Green and Carol (1984) in the transverse plane, positioned at a height which approximates the axis of the sub-talar joint (figs 5.2 and 5.3). Tests on the frame and ad/abduction and dorsi/plantarflexion footplates suggest that they are capable of similar accuracy.



bisection axis



deviated axis

Fig 5.3. Deviated axis.

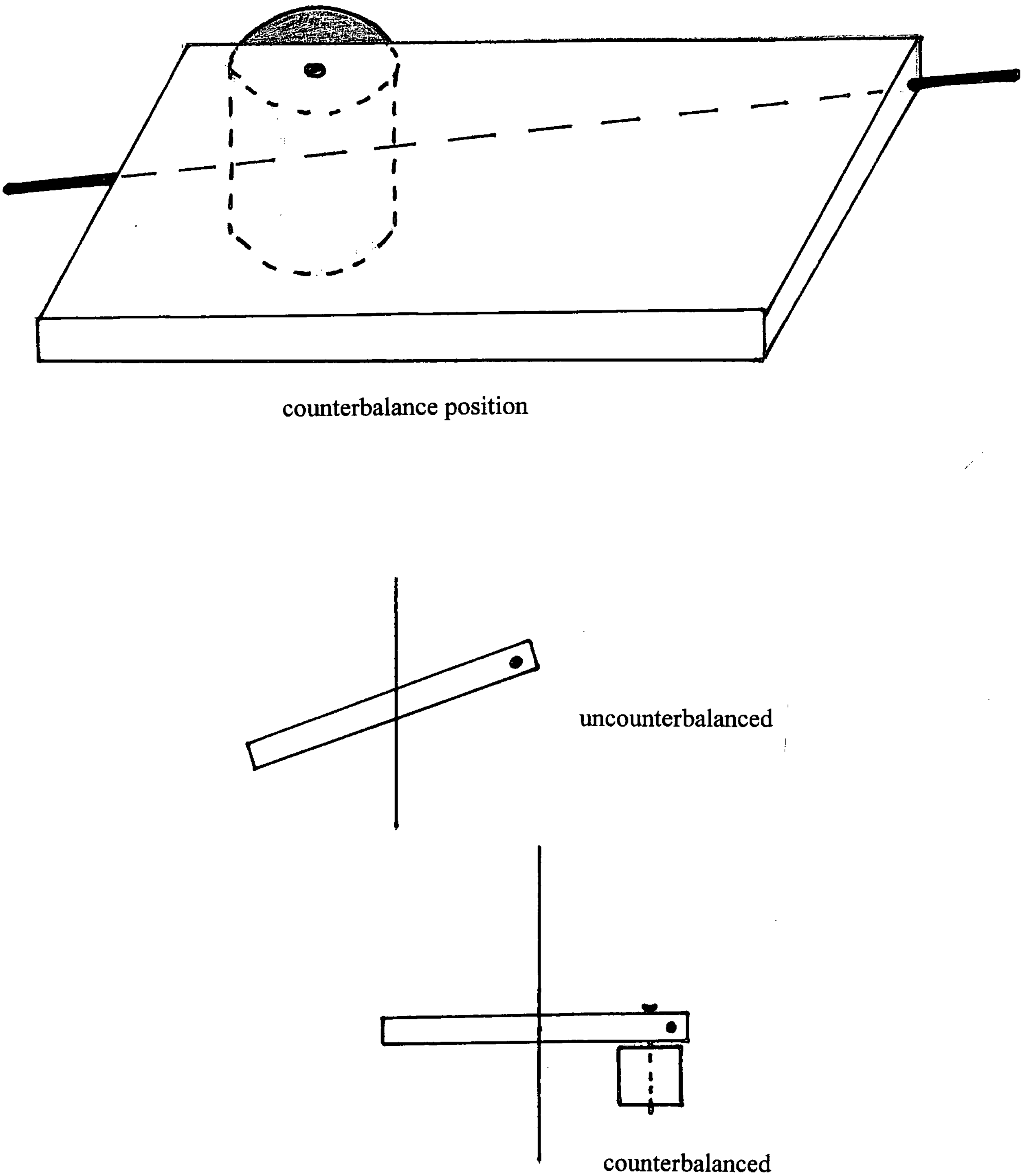


Fig 5.5. Footplate counterbalance.

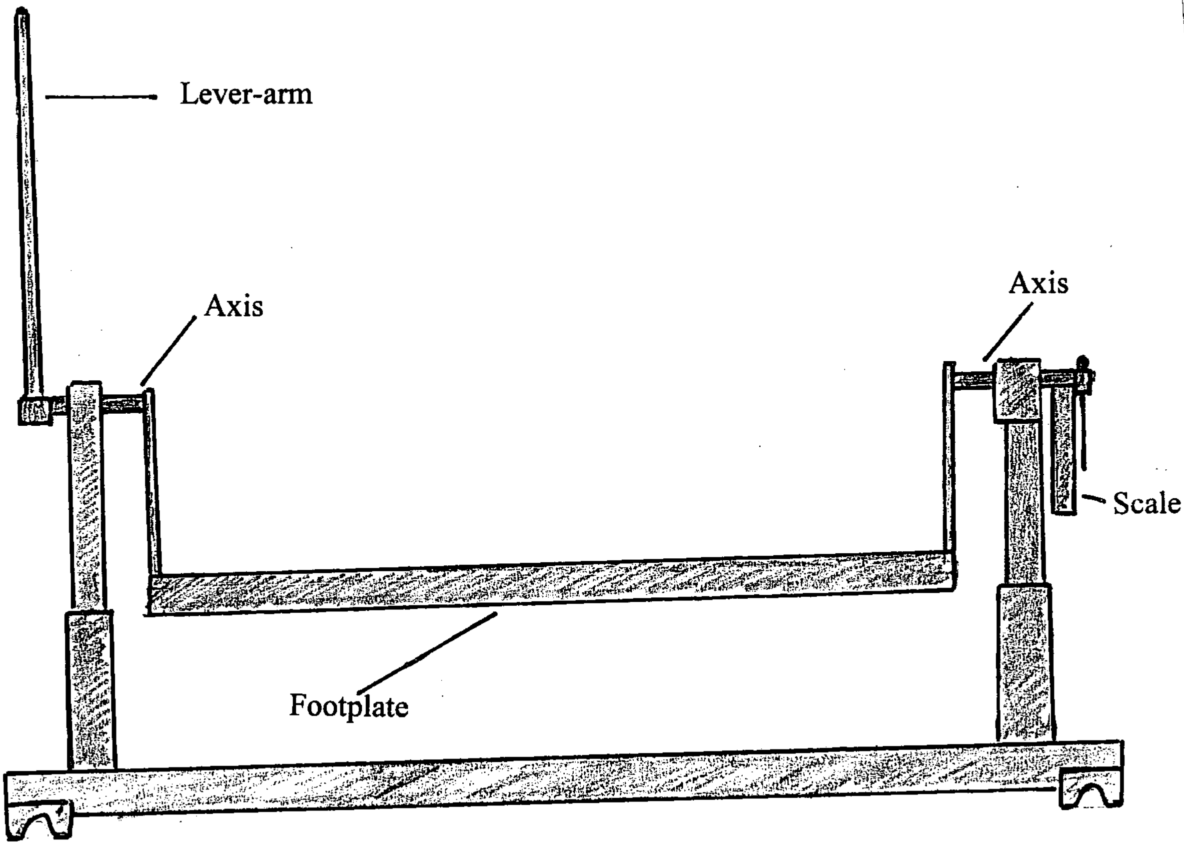


Fig 5.4. Footplate and lever-arm assembly.

5.3 Counterbalanced footplate.

With an axis deviating 16 degrees in the transverse plane a weight bias was introduced which inverted the unloaded footplate. It was found that this increased the amount of inversion before torque was applied, and a 950 gram counterbalance was attached to the footplate to counteract this and allow the unloaded footplate to remain horizontal (figure 5.5).

5.4 Measurement of range-of-motion.

Range-of-motion in each cardinal body plane was measured using a separate footplate attached to the rig. During initial tests with a prototype rig, using a constant seat height of 72cm, which is the average height of a hospital treatment plinth, 6 subjects were measured using a hand-held protractor and unknown torque. Measurements showed a wide variation of range-of-motion, and could not be considered accurate although they did show that the rig was capable of differentiating between measurements for different subjects. The prototype rig was altered to include protractors which were capable of measuring range-of-movement in degrees in each body plane, and a spring balance which would allow a known torque to be applied.

Difficulty was initially encountered when reading values, since the prototype rig had protractors placed at right angles to the axis of the range-of-motion, which were at the back or side of the rig. Great difficulty was encountered trying to read measurements while applying torque to the footplate and the following adaptations were carried out: The ad/abduction footplate was modified to include a transparent perspex top which was marked and calibrated in 5 degree divisions. A new scale was marked and calibrated in 5 degree divisions for the dorsi/plantarflexion footplate. This was incorporated into the footplate front support, and allowed dorsiflexion and plantarflexion values to be collected from the front of the rig. The in/eversion footplate was modified so that the scale was at the front of the rig.

5.5 Applying a known torque.

To allow the experiment to be replicated, a known torque range was applied for each measurement. This was applied by the tester pulling a calibrated spring balance which was connected to a steel rod attached to the ball-joint pivot at the axis of the footplate. Care was taken to maintain a 90 degree angle between the steel rod and the spring balance when torque was applied.

Initially the torque applied was 8Nm. This was chosen arbitrarily, although in a similar study Ball was able to demonstrate that a torque of approximately 7Nm was necessary to produce maximum passive motion of the hindfoot (1994). He further found that no further movement occurred when the torque was increased, and that no discomfort was experienced by any of the subjects (N = 5) even when the torque was increased to 10Nm.

In this study mean inversion measurements obtained from a group of subjects (n = 8) using 8Nm were higher than reported in similar, recent studies (Allinger and Engsberg (1992) and Ball and Johnson (1996)). The applied torque was reduced to just below 4 Nm, calculated by 2.65Kg x the length of the steel rod connected to the pivot (1.50 metres) 9.81 (gravity) = 3.89 Nm.

Values obtained using 3.9 Nm were considered to be useful, in that they were higher than other published studies, due to the position of the axis about which the torque was applied. At 8 Nm it was found that unwanted movement occurred in the leg, suggesting that the ankle joint complex was at its end of range of motion and locking.

	Start	inversion	Eversion	ROM
3Nm	20 degs	40 degs	30 degs	70 degs
3.9Nm	20 degs	45 degs	30 degs	70 degs
8Nm	20 degs	50 degs	30 degs	80 degs

Comparison of values obtained when different torques were applied.

Lower applied torque reduced unwanted movement of the lower leg which was quantified by attaching a plastic shield with a 10mm window cut into it to the frame. The shield was pressed over the shin once the leg was placed in the rig, so that the area of skin inside the window could be marked. Care was taken to ensure that the marked skin remained inside the window while torque was applied.

The final rig set-up incorporated the following features:

Comfortable, adjustable clamps to hold the subject's leg securely.

An easy-to-read scale in degrees.

A counterbalanced footplate.

A footplate which could accomodate and hold securely normal adult foot sizes.

A lever/spring balance mechanism which allowed a known torque to be applied.

CHAPTER SIX

RIG EXPERIMENTAL PROCEDURES.

This chapter describes experimental, reliability and repeatability studies carried out to determine accuracy of the measuring rig and operator technique.

Measurements were taken by one operator and subjects were studied to show whether:

(i) there was a difference in ROM when the axis was moved from a position which bisected the footplate, to one which deviated from the bisection by 16 degrees.

(ii) the difference, if any, in ROM when the footplate was counterbalanced.

(iii) the difference, if any, in ROM when different torques were applied to a known axis.

6.1.1 Reliability.

Ten measurements were carried out to establish reliability of the rig and measurement methods.

One subject (age 27) was tested by the same person between 10am and 12pm on ten different days, leaving at least two days between tests. The rig was set up with no counterbalance on the footplate and an axis which deviated 16 degrees medially. a constant torque of 8Nm was applied to obtain the results.

Table 6.1.

	Start	Inv	Ev	ROM
Mean	30.5 degs	28 degs	29.5 degs	57.5 degs
SD	2.83	2.58	1.58	3.53
C of V	9.27%	10.85%	5.35%	6.13%

Reliability test results.

Table 6.1 shows Coefficient of Variation values generally less than 10%, indicating that both the rig and the measurement methods were reliable.

6.2 Repeatability.

Four sets of measurements were carried out on eight subjects, mean age 28 (SD = 6.7) to establish repeatability of the procedure.

Each subject was tested by the same person on four different occasions. The rig was set up with an uncounterbalanced footplate and an axis which deviated 16 degrees medially. a torque of 4Nm was applied in each case.

Table 6.2.

Subject	Mean ROM	SD	Co of Var
1	46.2 degs	4.78	10.34%
2	52.5 degs	6.45	12.40%
3	73.7 degs	7.5	10.10%
4	62.5 degs	6.45	10.40%
5	75 degs	5.7	7.60%
6	118,7 degs	8.53	7.18%
7	42.5 degs	5	11.76%
8	41.2 degs	2.5	6.06%

Repeatability values

The mean of the repeatability ROM values were similar to both the reliability subject mean ROM and control group ROM. (table 6.5).Coefficient of variation values for repeatability ROM were generally below 10% (mean 9.48%), indicating that experimental procedures using this rig were capable of being repeated.

6.3 Axis position.

In order to compare the ranges of motion about an axis of rotation inclined at 16 degrees medially (Manter (1941)) and one which bisects the foot (Inman (1976)). 15 normal subjects were tested first using a 16 degree axis and then using the axis which bisected the foot. The subjects who had a mean age of 23 (SD 6.4), had no history of ankle problems or disease affecting the lower limb. In both configurations a torque of 4Nm was applied to the footplate with the subject's foot firmly strapped to the footplate and the angular displacement measured on the protractor scale. This was repeated in both inversion and eversion once for each subject.

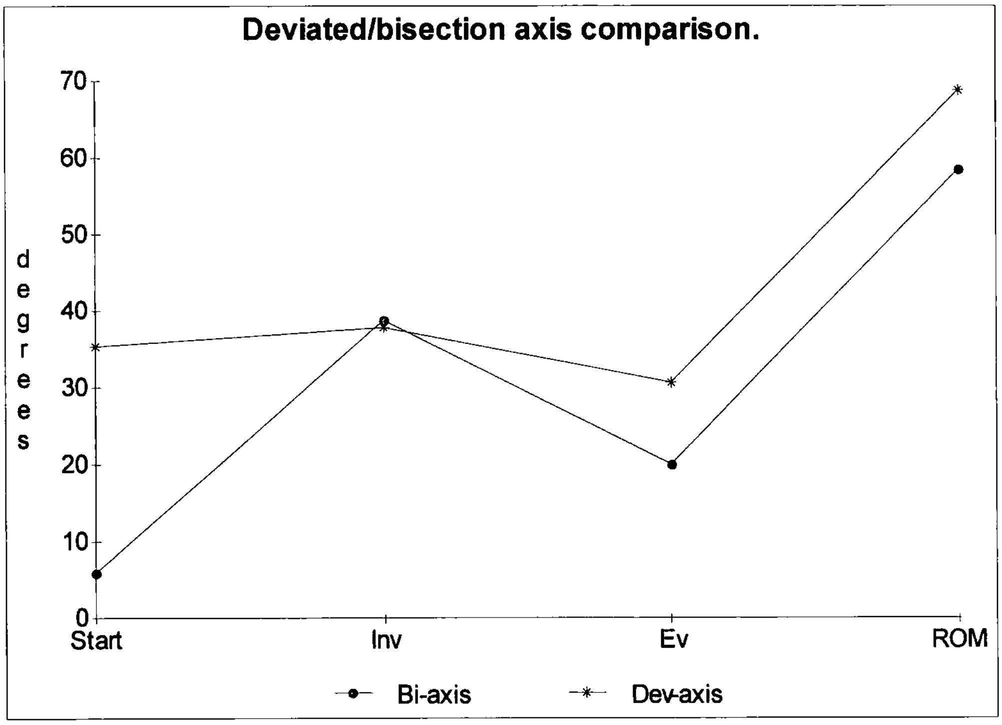


Chart 6.2 Comparison of the influence of the axis of rotation on inversion-eversion.

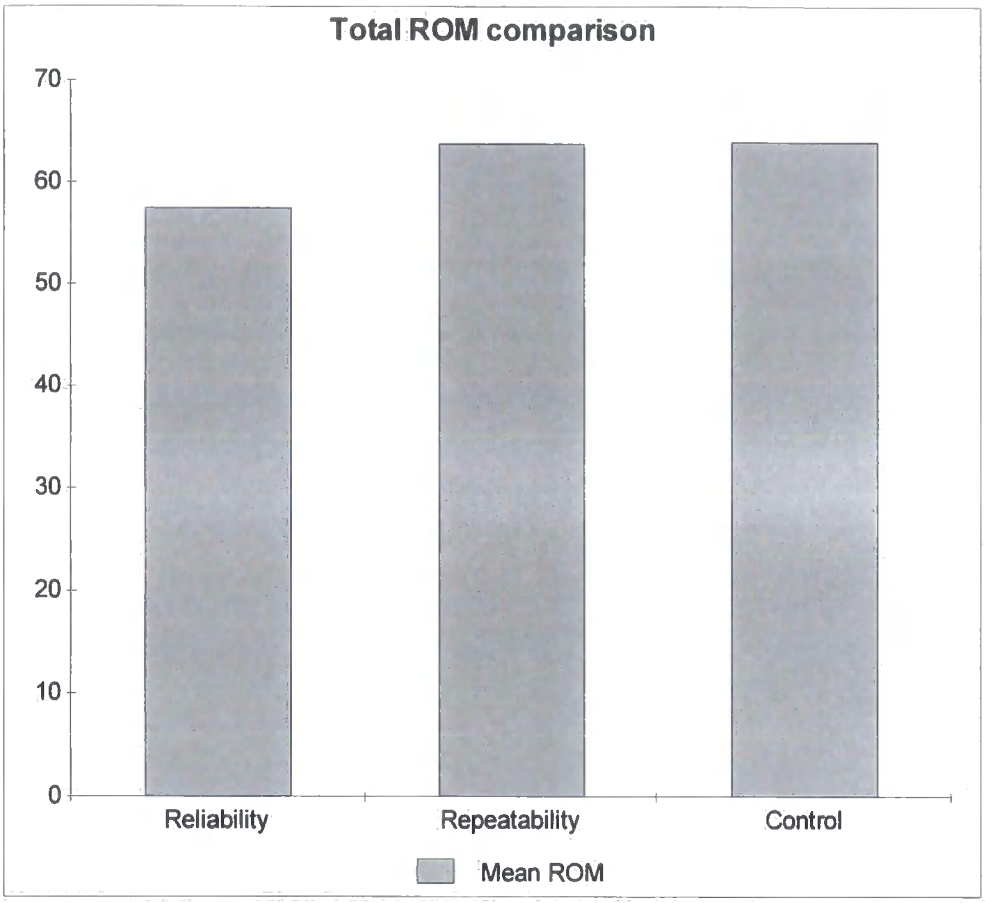


Chart 6.1 Comparison of the influence of the axis of rotation on inversion-eversion.

Table 6.3.

	Start	Inv	Ev	Total inv	ROM
Dev axis	35.31 degs	37.8 degs	30.62 degs	72.5 degs	68.75 degs
Bisect axis	5.93 degs	38.75 degs	20 degs	44.37 degs	58.43 degs

The results clearly show a significant difference in the start position (mean 30 degrees) and a difference in overall ROM (10 degrees). It would seem more movement is available for a given torque around an axis deviated medially by 16 degrees, than an axis which bisects the foot.

6.4 Counterbalanced versus non-counterbalanced footplate

By moving the axis to 16 degrees medially from the centreline, the footplate was no longer symmetrical and hence a residual torque was applied to the ankle simply by virtue of this asymmetry. To counteract this a balance was applied to the footplate. Using first the uncounterbalanced footplate and then the counterbalanced footplate a torque of 4Nm was applied to one subject (age 49) ten times each. Measurements were taken over a two-week period with one counterbalanced and one uncounterbalanced measurement taken daily. These data were used to study the reproducability of the results, both with and without the counterbalance.

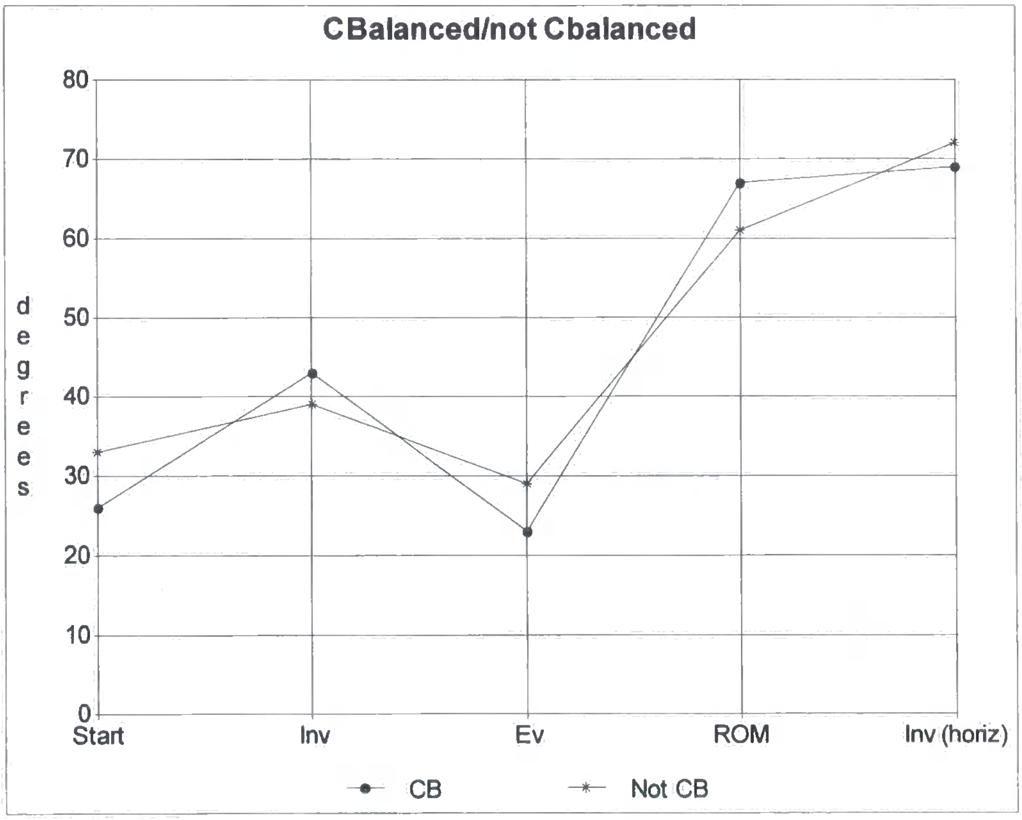


Chart 6.3 Counterbalanced versus non-counterbalanced footplate.

Table 6.4.

	Start	Inv	Ev	ROM	Inv (horiz)
Mean	26 degs	43 degs	23 degs	67 degs	69
SD	3.1	5.7	4.2	2.6	3.6
Co of Var	11.9	13.3	18.3	3.9	5.3

Readings taken with counterbalance.

Table 6.5.

	Start	Inv	Ev	ROM	Inv (horiz)
Mean	33 degs	39 degs	29 degs	61 degs	72 degs
SD	2.5	3.9	3.9	18.9	3.4
Co of Var	7.8	10.1	13.5	3	4.8

Readings taken without counterbalance.

Mean Start position with the uncounterbalanced footplate was almost 10 degrees higher (table 6.2 and 6.3 and chart 6.2), reflecting additional torque imposed by the weight of the footplate around the deviated axis. Other mean measurement comparisons were nearer 5 degrees, and the inversion from horizontal comparison was within 5 degrees.

6.5 Comparison of results when three different torques were applied.

Using the same rig and footplate set-up, with the axis deviated medially and the footplate counterbalanced, 12 subjects, mean age 23 (SD= 5.6) were measured using two different torques, 3Nm and 8Nm. These were compared with the control group which utilised the same rig and footplate set-up viz; a counterbalanced footplate and a standard torque of 4Nm. As expected, start positions (equilibrium position with no torque applied) were similar, and higher than the control group. Inversion and total range of motion values were higher in both cohorts and the control group the more torque applied, eversion values were similar.

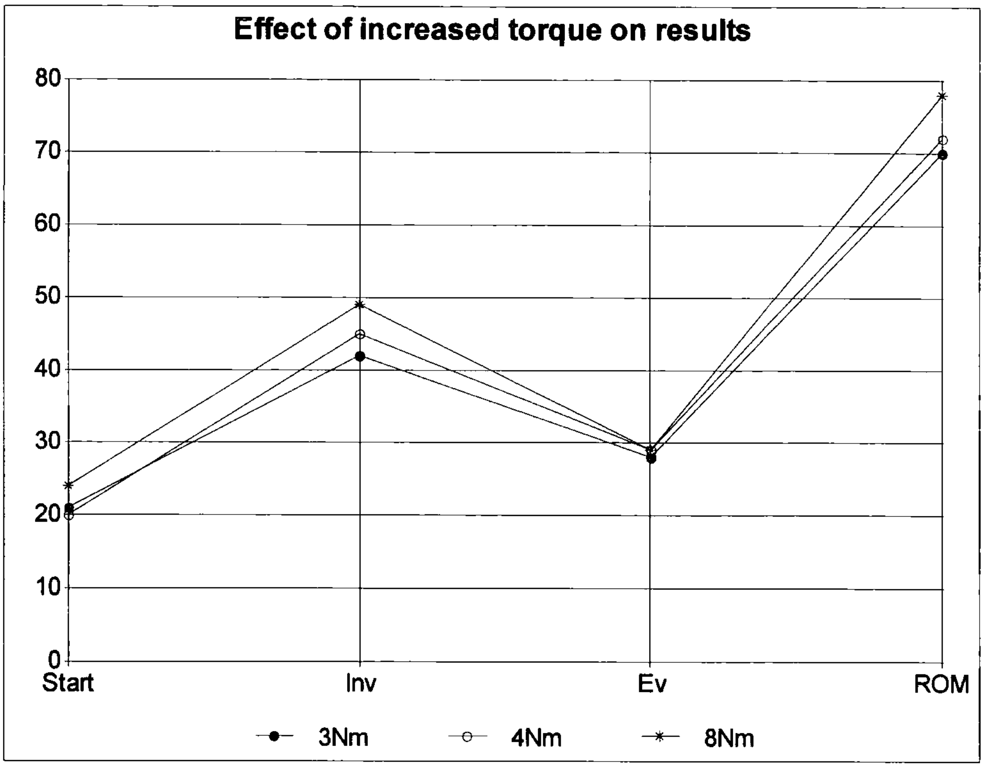


Chart 6.4 Comparison of results when three different torques are applied.

Table 6.6.

	Start	Inv	Ev	ROM
3Nm	22	42	28	70
4Nm	20	45	29	72
8Nm	24	49	29	82

Torque and degrees ROM obtained.

6.6 Comparison of results when three different torques were applied.

It would seem that the ROM increases with increased torque, as one would expect. Eversion is similar whether 3, 4, or 8Nm of torque is applied, largely because there is more anatomical resistance to eversion than inversion, the main structures responsible being the anterior tibio-fibular ligament, the calcaneocuboid articulation and the plantar aponeurosis.

6.7 Conclusions.

The rig was shown to be reliable (table 6.1) and it was demonstrated that measurements were capable of being repeated (table 6.2).

Axis.

The position of the axis about which rotations were made was important since an axis which deviated 16 degrees medially allowed an increased start (equilibrium) position and a higher eversion and final ROM value when a torque of 4Nm was applied (chart 6.1).

Counterbalance.

An experiment was carried out to compare the effects of counterbalancing the footplate. Comparison measurements were taken with the footplate counterbalanced and uncounterbalanced. The counterbalanced measurements showed a lower start (equilbrium) position, due to the counterbalance negating the effect of the asymmetrical footplate. However once a torque was applied to the counterbalanced footplate, inversion and total ROM values were within 5 degrees of those obtained with the uncounterbalanced footplate while eversion was 6 degrees lower (tables 6.4 and 6.5).

Although Coefficient of Variation figures were higher for measurements obtained with the counterbalanced footplate it was felt that these were still within acceptable limits. Additionally the counterbalanced footplate allowed a more accurate measurement of start (equilibrium) position.

Torque.

Three different torques were applied to a counterbalanced footplate and the results compared. High inversion and total ROM values were found with an applied torque of 4Nm (table 6.6) and a decision was taken to use this torque for the experiments, since a higher torque would inevitibly contribute to lower leg movement within the rig frame, causing discomfort to the subjects and giving a false higher ROM value.

It is interesting to note that eversion values remained almost the same irrespective of the torque applied (chart 6.4) and it was felt that this was due to anatomical restrictions around the AJC, principally from the anterior tibio-navicular ligament, the calcaneocuboid articulation and the plantar aponeurosis.

CHAPTER SEVEN

MEASUREMENT OF FRONTAL PLANE MOTION

Four experiments were carried out to examine the following:

(1) Equilibrium position and ROM in a normal population (n = 100).

(2) Diurnal variation (n = 7).

(3) The difference in ROM when the same torque was applied around a deviated axis as opposed to an axis which bisected the footplate (n = 15).

(4) Any difference in ROM between subjects presenting with localised non-traumatic foot pathology (n = 10) and localised non-traumatic lower limb pathology (n = 10).

7.1 The control group.

One hundred normal subjects of both sexes, of mean age 24.6 (range = 18-49) were measured to find:

(a) Start or equilibrium position.

(b) Inversion from Start position.

(c) Eversion from Start position.

(d) Total ROM.

(e) Total Inversion (calculated from footplate horizontal position).

7.1.1 Subject inclusion criteria.

The sample population was randomly selected from undergraduate students of both sexes at the Durham School of Podiatry. Subjects with any systemic or localised joint disease were excluded from the study. Informed consent was obtained before data collection commenced. Measurements with a counterbalanced footplate were taken between 10.00 am and 12.00 pm.

Coronal plane range-of-motion of the ankle joint complex was measured using a constant seat height of 72cm and the purpose-built rig which held the leg and foot securely, and applying 4Nm of torque. This allowed measurements to be taken which were accurate to within 5 degrees. The footplate had an axis which deviated medially by 16 degrees in the transverse plane. All statistics were computed in actual recorded values although rig sensitivity limitations ($\pm$ 5 degrees) are recognised. The Shapiro-Wilk test was applied to test for normal distribution.

7.1.2 Results.

Table 7.1.

Variable	Mean	SD	Skewness	Kurtosis	P	Distribution
Start	19.5	5.14	0.3011349	3.507755	0.44257	Not normal
Inv	44.9	10.98	0.2494697	2.492367	0.83564	Normal
Ev	21.35	4.81	0.5322614	3.2324	0.0776	Normal
ROM	66.15	11.52	0.1352645	2.51758	0.7241	Normal
T Inv	64.4	10.64	0.0824667	2.237317	0.81672	Normal

It can be seen from table 7.1 that each variable fell within normal distribution apart from the Start (equilibrium) position which was shown to have a non-normal distribution by high Skewness and Kurtosis values.

7.2 Diurnal variation.

Seven subjects of both sexes, of mean age32.5 (range 24-48) were measured at two-hourly intervals from 7.00 am to 9.00 pm to investigate the existence of any diurnal variation in coronal plane ROM at the ankle joint complex.

7.2.1 Subject inclusion criteria.

Subjects were selected using the following criteria:

(a) Availability from 7.00 am to 9.00 pm at two-hour intervals.

(b) No systemic or localised joint disease.

(c) Age range within the Control Group age range.

Using a constant seat height of 72cm, the purpose-built rig and applying a torque of 4Nm, three measurements were taken every two hours, and four values obtained.

Start position, Inversion, Eversion and ROM.

Table 7.2.

	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6	Subject 7
Start(mean	20.62	20.87	17.62	17.62	17.5	17	24.37
Start (SD)	2.19	2.41	1.84	1.99	2.2	2.39	2.44
Inv (mean)	36.12	43.37	40.75	45.62	35.87	41.37	51.75
Inv (SD)	2.64	2.72	2.65	2.61	2.29	2.06	3.01
Ev (mean)	22.75	22.75	26.37	20.75	27.25	23	18.75
Ev (SD)	12.81	1.28	2.77	3.61	2.81	3	2.12
ROM (mea	58.87	66.12	67.12	65.1	61.87	64.37	70.5
ROM (SD)	3.18	2.53	5.24	4.76	3.39	4.24	3.81

Diurnal variation means and standard deviations.

7.2.2 Results.

Analysis of Variance statistical tests were applied and these showed a significant difference in measurement for each variable at each time interval for all subjects **(appendix 1b).**

7.3 Axis orientation comparison.

Fifteen normal subjects of both sexes, of mean age 27 (range 18-43) were measured to find:

(a) Start or equilibrium position.

(b) Inversion form Start position.

(c) Eversion from Start position.

(d) Total ROM.

(e) Total Inversion (calculated from footplate horizontal position).

7.3.1 Subject inclusion criteria.

The sample population was randomly selected from undergraduate students of both sexes at the Durham School of Podiatry who were part of the control group. Measurements were taken between 10.0am and 12.00 noon. Subjects with any systemic or localised joint disease were excluded from the study. Informed consent was obtained before data collection commenced.

Torque.

Coronal plane range-of-motion of the ankle joint complex was measured using a constant seat height of 72cm, the purpose-built rig and applying 4Nm of torque. Four Nm of torque was applied around an axis which bisected the footplate in an anterior/posterior direction. These results were compared with earlier results from the same subjects who were part of the control group.

7.3.2 Results.

Statistical values were computed using t-tests to compare the results of Start, Inversion, Eversion and Range of Motion (ROM).

Table 7.3.

Variable	Mean	SD
Deviated	34.86	4.32
Bisected	6	4.07

Start

The p-value was 0.000. This shows a significant difference between cohorts.

Table 7.4.

Variable	Mean	SD
Deviated	37.13	8.65
Bisected	38.46	7.16

Inversion

The p-value was 0.6492. This indicates no significant difference between cohorts.

Table 7.5.

Variables	Mean	SD
Deviated	29.73	8.36
Bisected	19.66	4.8

Eversion

The p-value was 0.0004. This indicates a significant difference between cohorts.

Table 7.6.

Variables	Mean	SD
Deviated	66.86	10.54
Bisected	58.13	9.6

ROM

The p-value was 0.0248. This indicates a significant difference between cohorts.

7.4 <u>Pathologies distal and proximal to the ankle joint complex.</u>

Twenty subjects of both sexes, of mean age 47 (range 25-68) were measured to find

(a) Start or equilibrium position.

(b) Inversion from Start position.

(c) Eversion from Start position.

(d) Total ROM.

7.4.1 Subject inclusion criteria.

The sample population was selected from patients attending the Podiatry clinic at the Washington BUPA hospital. 20 patients with no history of joint or systemic disease who presented with mild, non-traumatic pathology were split into two cohorts. Those with mild pathology distal to the talo-crural joint (n = 10), and those with mild pathology proximal to the talo-crural joint (n = 10). Each cohort was measured using a constant seat height of 72 cm, the purpose-built rig and 4Nm of torque, and the results compared. Ethics Committee approval was granted before the study commenced and informed consent was obtained before data collection.

7.4.2 Results.

Measurement values of Start, Inversion, Eversion and Range of Motion of the two cohorts were compared using t-tests.

Table7.7.

Variable	Mean	SD
Distal	23.2	3.96
Proximal	20.8	5.69

Start

The p-value was 0.0939. This shows no statistical difference in the **Start** values.

Table 7.8.

Variable	Mean	SD
Distal	42.1	5.56
Proximal	42.5	6.58

Inversion

The p-value was 0.8283. This shows no statistical difference in the **Inversion** values.

Table 7.9.

Variables	Mean	SD
Distal	25.4	4.92
Proximal	24.2	5.28

Eversion

The p-value was 0.6059. This shows no statistical difference in **Eversion** values.

Table 7.10.

Variables	Mean	SD
Distal	67.5	7.02
Proximal	65.7	7.86

ROM

The p-value was 0.5959. This shows no statistical difference in **ROM** values.

CHAPTER EIGHT

DISCUSSION

8.1 Diurnal variation.

Circadian and diurnal variation in joint stiffness is a well recognised phenomenon (Yung *et al* (1984)). In this study it was important to quantify diurnal variation of ROM of the ankle joint complex since a high variation could have affected the reliability of the control measurements. The highest mean difference of diurnal variation was 3.75 degrees (Start position), and the highest mean diiference of diurnal variation between 9.00AM and 1.00PM was 3 degrees (Eversion position). It was felt that although there was a significant difference in diurnal variation this did not affect the study outcome since all measurements were taken during the day between 10.00AM and 12.00PM and rig accuracy limits were set at $\pm$ 5 degrees.

8.1.1 Hypothesis 1.

A statistically significant mean diurnal variation occurs in the range of passive motion occurring at the ankle joint when 4Nm of torque is applied around an axis which deviates medially by 16 degrees in the transverse plane, when readings are taken a 2-hour intervals.

Analysis of Variance statistical tests showed a significant difference in measurement for each variable at each time interval in all subjects and therefore this hypothesis is accepted.

8.2 The rationale for using a rig axis which deviates medially.

Work carried out by other researchers which examined range-of-motion at the sub-talar joint either applied a known torque to an axis which bisected the foot (Ball and Johnson (1996)), applied an unknown torque to an axis which deviated 16 degrees in the transverse plane and 42 degrees in the sagittal plane, as described by Green and Carol (1984) and Alexander *et al* (1982), or utilised active movement which could not be measured (Allinger and Engsberg (1992)) (table 7.1). With no uniform methodology, published maximum range-of-motion of coronal plane motion of the ankle joint complex varies between 25 degrees and 73 degrees.

Table 8.1.

Alexander	*et al*	1982	unknown	no	yes	73 degrees
Bailey	*et al*	1984	unknown	no	yes	25 degrees
Allinger an	Engsberg	1992	unknown	yes	no	29 degrees
Ball and	Johnson	1996	10Nm	no	yes	48 degrees
Holland		1999	4Nm	no	yes	66 degrees

AJC measurement diversity of methods and results.

8.3 Hypothesis 2.

The mean total passive range of motion available when a known torque is applied at the ankle joint complex is significantly different when the torque is applied to an axis which deviates 16 degrees medially in the transverse plane than when applied to an axis which bisects the foot.

Measurements were significantly different for each variable apart from Inversion and therefore this hypothesis is accepted.

Utilising an axis which deviated 16 degrees medially from a longitudinal bisection of the foot, and applying 4Nm of torque, the findings of this study suggest that the maximum range-of-motion of inversion in the healthy human foot is in excess of 60 degrees, although it is recognised that a small amount of mid-tarsal joint motion probably contribited to this. When the same rig was adjusted to accomodate an axis which bisected the foot, and the same torque was applied, a mean of 45 degrees of inversion was found.

Additionally it was noticable that when torque was applied to a bisected axis the leg tended to move, which was not the case when the same torque was applied to a deviated axis.

8.3.1 Deviated/bisection axis comparison values

The deviated axis total inversion values, which are slightly higher than the control group, are much higher than the bisected axis. This value was computed by adding the start position value to the inversion value obtained after 4 Nm of torque had been applied.

The difference in inversion between the deviated axis (37.8 degrees) and the bisection axis (38.75 degrees) may be explained by by rig accuracy limitations. The fact that there was little difference in the deviated axis cohort between the start position (35.31 degrees) and inversion (37.8 degrees) once 4Nm of torque had been applied may have been due to the limits of accuracy of the rig ($\pm$ 5 degrees) and the probability that 40 degrees was the physiological end of ROM for that particular group.

8.4 Hypothesis 3.

A statistically significant difference is present in the amount of inversion and eversion occurring at the ankle joint complex in patients who present with localised non-traumatic lower limb pathology, and localised non-traumatic foot pathology.

No statistical difference was shown in any of the above measurements and therefore this hypothesis is rejected.

8.4.1 Ankle joint complex axes pitch.

It has been discussed how combined talocrural joint axis and sub-talar joint axis (making up the ankle joint complex axes) may be high or low pitched, and how a low-pitched axis will cause excessive frontal plane motion, while a high-pitched axis will cause excessive transverse plane motion (Green and Carol (1984)). Implicit in this theory is the suggestion that excesssive movement in the frontal plane may cause a predisposition for foot pathology while excessive movement in the transverse plane may cause a predisposition for pathology proximal to the ankle joint complex.

Tests carried out on twenty subjects with non-traumatic, non-systemic (and therefore with etiology which can be safely assumed to be at least in part mechanical) mild pathologies affecting sites either proximal or distal to the ankle joint showed no significant differences in frontal plane range-of-motion available at the ankle joint complex.

8.5 The equilibrium position of the foot at rest.

The study found that with the leg held securely in the rig so that it was perpendicular to the ground, and the foot strapped in the footplate at 90 degrees to the leg, the foot moved into inversion (mean 19.5 degrees). Anatomically ligaments, osseous articulations and the plantar aponeurosis combine to allow more inversion than eversion, while anatomical resistance to eversion is provided primarily by the anterior tibio-navicular ligament, the calcaneocuboid articulation and the plantar aponeurosis. It is important to note that statistical testing using a Shapiro Wilks Test showed a non-normal distribution curve (skewness = -.30, kurtosis = 3.50).

A mean equilibrium inversion value of 19.5 degrees is probably clinically important since it infers that for a subject to stand and ambulate on a flat unyeilding surface the foot must evert to allow the plantar surfaces to contact the ground medially and laterally. It would seem that the foot can do this in two ways. If there is sufficient eversion available at the ankle joint complex the calcaneus will evert; if there is not sufficient eversion available at the ankle joint complex the calcaneus will remain vertical or, as in Pes Cavus, slightly inverted and eversion will take place at the level of the mid-tarsal joint and particularly the calcaneocuboid joint.

8.6 Healthy foot function

The healthy human foot is capable of the following:

Adaptation, either for support, or for slow or rapid ambulation.

The healthy human foot is capable of:

Adaptation, either for support, or for slow or rapid ambulation.

Functioning on most solid or semi-solid terrains including sand, rough terrain and hard horizontal surfaces such as concrete.

Aiding near-vertical climbing, including rock faces and trees (coconut palms).

Allowing these activities to be undertaken successfully by subjects of widely varying weights and strengths.

Authorities are not in agreement as to what is a normal foot and what type of foot requires treatment (Pratt and Sanner (1996), Walker (1994)) and it is probable that some of the conditions which are currently regarded by podiatrists and others (Pratt (1995), Nawoczenski *et al (*1995)) as requiring treatment are simply variations of normal, distortion of the heel or foot being compensatory changes to allow the foot to weightbear on a hard, flat surface.

8.6 Perpendicular ambulation, age and terrain.

Little attention has been made in the literature of the hard, unyeilding surfaces which individuals in Western civilization live on for the majority of their lives, although McRae, when describing the position within the normal foot, of the calcaneus and first and fifth metatarsals, makes the point that this position is only adopted when the subject is standing on level ground (McRae (1990)). Susman and Stern (1982) showed how the bone structure of a fossil foot 1.5 - 2 million years old (coded 0H8) is essentially the same as modern day skeletal foot structure, while the almost complete skeleton of Homo Erectus (Nariokotome Boy), dated at 1.6 million years old, posesses similar lower limb skeletal geometry to modern man (figs 7.1 and 7.2).

Homo Erectus is generally accepted in anthropological terms as being Homo Sapiens distant ancestor. His limbs did not evolve for ambulation solely on hard horizontal surfaces, and it could be postulated that early bipedal hominids, like Homo Sapiens them unsurpassed adaptability to their environment as well as the ability to ambulate rapidly over undulating terrain.

The ramifications for civilized Homo Sapiens are that compensation to allow the foot to conform to a uniformly horizontal surface, yet allow the body to remain erect, must take place, either at the talocrural joint - or distal or proximal to it. The application of Wolff's Law (1892) in Nordin and Frankel (1989) would suggest that it simply becomes a matter of time before permanent physiological changes take place in the structure of the foot.

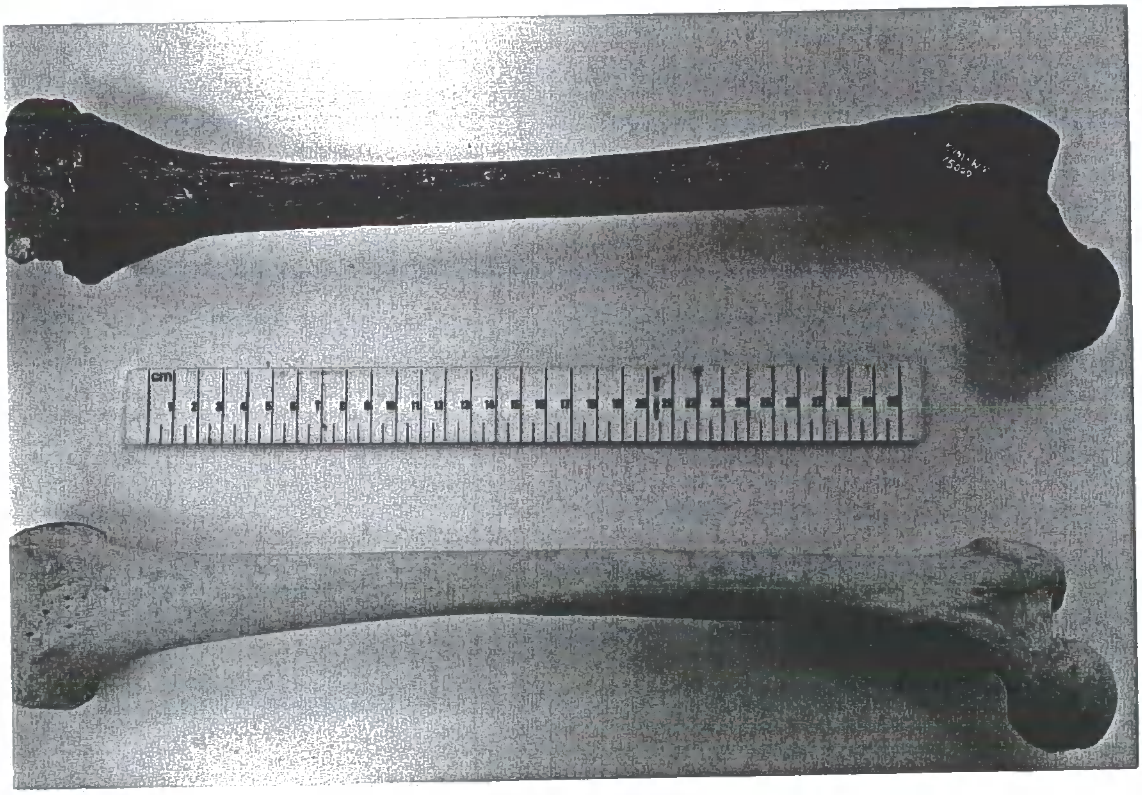


Fig 8.1 Homo Erectus/Homo Sapiens femur comparison.

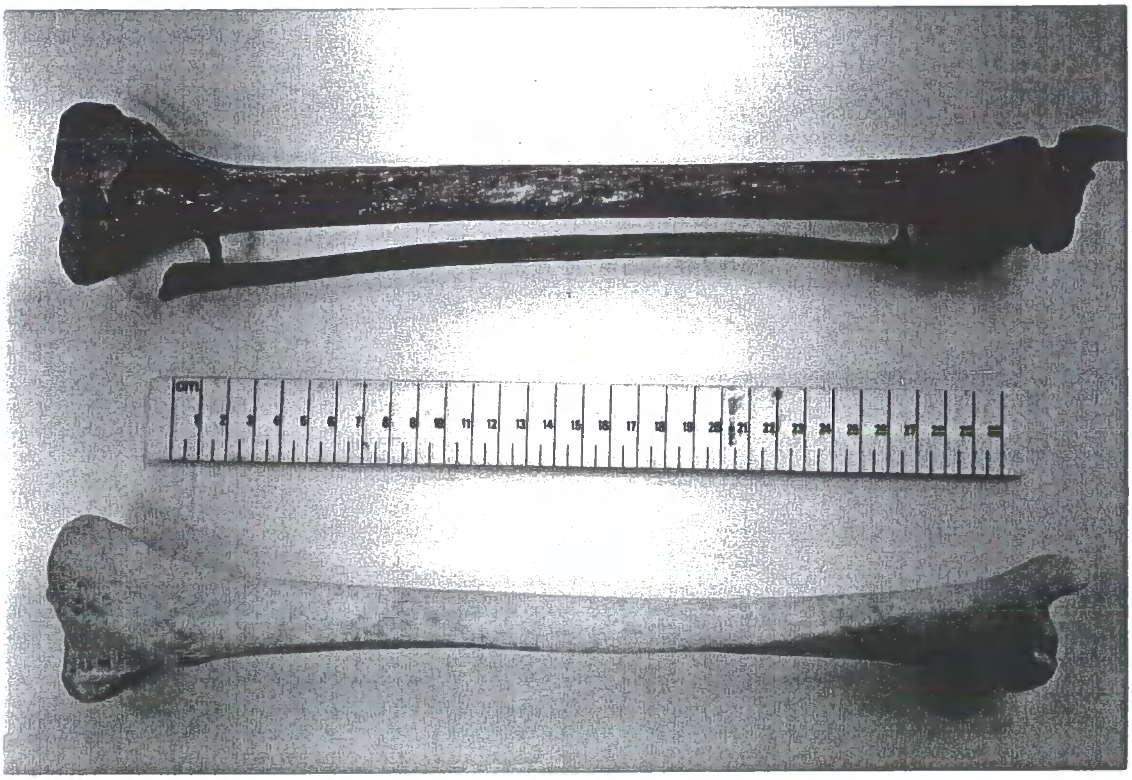


Fig 8.2 Homo Erectus/Homo Sapiens tibia comparison.

An examination of a random sample of non-weightbearing AP radiographs of the ankle (n=37, age range 7 -79, mean 33) revealed congruency of the talocrural joint with no long-term pathological changes in each case. This suggests that it is likely that any compensation necessary for the foot to conform to horizontal surfaces takes place mostly either distal or proximal to the talocrural joint, and that any long-term pathological changes in structure would also take place either distal or proximal to the talocrural joint.

In this study a mean equilibrium of 19.5 degrees of inversion was found. This would tend to suggest that an inverted foot in relation to the lower limb is normal, and that "normal" feet will have to compensate in order to weightbear and ambulate on uniformly hard, horizontal surfaces. This raises the question of whether civilised Homo Sapiens has evolved sufficiently for a life spent mostly on concrete.

It can be readily seen therefore that the healthy human foot is capable of a high degree of adaptation, able to support and carry varying loads over diverse terrain, and it is obvious that those feet with limited ROM (Pes Cavus) or increased eversion ROM (Pes Planus) at the ankle joint complex do not function as effectively, and are less able to adapt to different terrains. It is certain that the survival of Homo Erectus was a direct result of successful adaptation to his environment. It is equally certain that he passed some survival traits to his descendent, Homo Sapiens, and it is probable that a highly adaptable foot was one.

This study has described a rig design which is portable, mechanical (does not rely on electricity to operate) and is capable of yielding accurate results.

Recommendations.

There are three areas in which the author feels it would be useful to carry out further work. These are:

1. The question of high and low joint axis pitch, and the contribution this makes to potential mechanical injury site. There has been little scientific work carried out to support this theory, and it would be useful to carry out a controlled experiment with a larger cohort than was used in this work.

2. Equilibrium (inversion) position of the foot at rest. This study found a mean 19.5 degrees of inversion when the foot was strapped into a counterbalanced footplate. However the values were shown to be drawn from a non-normal distribution. Had this been a normal distribution it would have shown that many of the conditions which we currently regard as pathological are simply the foot adapting to a hard, flat surface. The author recommends that further work is carried out in this area, utilising a much larger cohort.

3. The functional foot orthoses single case study is unusual in that it presents objective data about changes in foot function. Traditionally imaging techniques, specifically x-ray, have been used post-surgery to measure structural changes in the foot, and this does not give a clear indication about altered foot function, improved or otherwise. A study using similar methods which examined several cohorts of subjects, each cohort with different presenting symptoms, would be helpful in two clinical areas.

A) It may help to establish the validity or otherwise of functional foot orthoses, using established scientific guidelines.

B) It may offer a means of evaluating foot function pre-surgery, providing clinicians with an alternative to surgical intervention for some patients.

CHAPTER NINE

CONCLUSIONS

9.1 Previous work in the field of measurement of range of-motion of the sub-talar joint was reviewed and revealed at least six different techniques and widely differing measurements. Factors which inhibit some of these studies being duplicated include unknown data collection methods, no uniform torque applied, and active movement of the joint being measured. After establishing that it is clinically impossible to separate sub-talar joint movement from ankle joint complex movement (Hinterman *et al* (1993)), a rig for measuring movement at the ankle joint complex was designed and tested.

Various rig parameters were tried and shown not to work as well as the final design, which incorporated easy-to-read scales, and the application of a known torque about an axis which deviated 16 degrees medially. The importance of this was demonstrated with an experiment which compared a deviated axis with a bisected axis. This showed that a higher ROM could be obtained for a smaller applied torque when a deviated axis was utilised. Although not ideal for routine clinical measurement due to its bulkiness, the rig design is ideal for accurate measurement of frontal plane range-of-motion in the laboratory or designated space, the only requirements being available light, and a clinic plinth.

Functional foot orthoses were discussed, as was the fact that prescribing protocols are not uniform and may change from clinician to clinician, and a single case study with supporting objective evidence was presented. A literature search revealed that most of the studies carried out into the effectivenes of orthoses were not scientifically controlled and a paucity of objective data was noted.

This study has shown that in normal subjects the ankle joint complex together with the mid-tarsal joint is capable of a higher ROM of inversion than has previously been thought. Further and possibly of more significance is that the study also found that if the leg is held perpendicular to the ground, with the foot held at 90 degrees to the leg, the foot will move into inversion. When ambulating on hard, flat surfaces the foot must evert to allow full contact, and the lower limb must internally rotate correspondingly.

It has been postulated that the pitch of the axes about which the ankle joint complex moves may predispose to pathology above or below the ankle (Green and Carol (1984)) although this study was unable to find any correlation between excessive frontal plane motion and pathology distal to the ankle.

The influence of diurnal variation on findings was measured and found to be significant, although falling within rig accuracy limitations ($\pm$ 5 degrees). An erratic pattern was identified and it was assumed that this was influenced by activity levels on a weightbearing joint.

Some authorities have denied that the normal foot has any effect on forces transmitted through the knee joint (Kettlekamp and Chao (1972), Goldberg *et al* (1989), Bindleglass *et al* (1993), Davidson (1993)), without, however, defining "normal" or "abnormal". Hinterman *et al* (1993) demonstrated how tibial rotations could be influenced by calcaneal eversion *in vitro*, while Olerud and Berg (1984) and others showed how frontal plane foot motion could change the valgus position of the knee *in vivo*. Clearly the active foot, healthy or otherwise, is capable of influencing knee motion and therefore forces acting around the knee joint.

Fossil specimens of Oh8 and Nariokotome Boy show a remarkable similarity to modern day lower limb and foot skeletal structure, and the high ROM of the ankle joint complex may be part of a survival feature passed almost unchanged from early hominids to present day Homo Sapiens, allowing him to weightbear and ambulate unshod on most types of terrain. The author found a mean 19.5 degrees of inversion when the leg was held in a position perpendicular to the ground, and the foot was allowed to move naturally into its equilibrium position. If further work shows that this is statistically significant it could be postulated that this is to allow the foot to work best on a mixture of soft and hard, flat and undulating terrain. Further, there is a strong possibility that the inverted foot may over time cause detrimental effects - not only on the structure of the foot, but also the knees, hips and spine.This is due to standing and walking on hard, flat surfaces for the majority of the time, as civilised man does, coupled with the application of Wolff's Law.

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Appendix 1.
Control group data.

Start	Inv	Ev	ROM	Total inv
20	45	20	65	65
20	30	20	50	50
5	65	15	80	70
20	55	25	80	75
15	60	15	75	75
15	50	10	60	65
15	60	15	75	75
25	55	25	80	80
20	40	20	60	60
20	65	20	85	85
10	40	15	55	50
25	60	25	85	85
15	70	15	85	85
20	50	20	70	70
20	55	20	75	75
25	50	25	75	75
15	65	15	80	80
20	30	20	50	50
20	40	15	55	60
25	50	25	75	75
25	35	30	65	60
20	40	20	60	60
25	45	25	70	70
20	40	20	60	60
20	30	20	50	50
10	70	20	95	80
25	45	25	70	70
20	20	20	40	40
20	40	15	55	60
20	50	20	70	70
20	65	30	95	85
20	35	20	55	55
20	40	20	60	60
25	35	25	60	60
20	30	20	50	50
10	45	15	60	55
20	50	25	75	70
15	55	25	80	70

Start	Inv	Ev	ROM	Total inv
15	35	20	55	50
10	70	20	90	80
25	35	25	60	60
20	35	25	60	55
30	40	30	70	70
10	45	15	60	55
20	45	20	65	65
35	45	35	80	80
10	60	15	75	70
20	30	15	45	50
20	30	20	50	50
25	40	20	60	50
20	30	20	50	50
10	30	15	45	40
20	40	20	60	60
15	35	20	55	50
25	40	30	70	65
15	55	25	80	70
25	35	30	65	60
20	55	25	80	75
20	40	20	60	60
10	50	15	65	70
25	55	30	80	80
20	35	20	55	55
20	50	20	70	70
10	40	15	55	50
15	35	15	50	50
15	50	20	70	65
20	50	20	70	70
20	45	20	65	65
20	30	20	50	50
20	50	25	75	70
20	45	20	65	65
15	55	20	75	70
25	50	30	80	70
25	35	20	55	60
25	45	25	70	70
30	40	35	75	70
20	50	25	70	75

Start	Inv	Ev	ROM	Total inv
20	50	20	70	70
25	35	25	60	60
20	35	20	55	55
20	35	20	55	55
25	35	30	65	60
20	50	20	70	70
20	45	25	70	65
20	30	30	60	50
20	50	25	75	70
20	30	20	50	50
25	25	25	50	50
20	50	20	70	70
25	50	20	70	75
10	60	15	75	70
20	50	20	70	70
25	30	25	55	55
15	50	20	70	65
15	45	20	60	65
20	60	20	80	80
20	35	20	55	55
25	50	25	75	75
20	55	15	70	75
10	50	20	70	60

Appendix 1(a).
Diurnal variation group data.

Time	Start	Inv	Ev	ROM
07:00 AM	19	33	22	55
09:00 AM	20	39	24	63
11:00 AM	17	38	23	61
01:00 PM	21	34	21	55
03:00 PM	24	35	24	59
05:00 PM	23	33	23	56
07:00 PM	21	38	24	62
09:00 PM	20	39	21	60

Time	Start	Inv	Ev	ROM
07:00 AM	19	43	24	67
09:00 AM	23	44	21	65
11:00 AM	21	48	23	71
01:00 PM	17	44	22	66
03:00 PM	19	38	24	62
05:00 PM	24	43	24	67
07:00 PM	23	43	23	66
09:00 PM	21	44	21	65

Time	Start	Inv	Ev	ROM
07:00 AM	17	39	26	65
09:00 AM	16	43	29	72
11:00 AM	19	41	28	69
01:00 PM	16	36	21	57
03:00 PM	17	39	24	63
05:00 PM	21	41	28	69
07:00 PM	19	44	29	73
09:00 PM	16	43	26	69

Time	Start	Inv	Ev	ROM
07:00 AM	16	43	21	64
09:00 AM	19	49	24	73
11:00 AM	15	44	16	60
01:00 PM	16	43	17	60
03:00 PM	19	45	19	64
05:00 PM	21	44	26	70
07:00 PM	18	48	24	62
09:00 PM	17	49	19	68

Time	Start	Inv	Ev	ROM
07:00 AM	16	34	26	60
09:00 AM	19	33	29	62
11:00 AM	17	39	24	63
01:00 PM	15	36	25	61
03:00 PM	16	34	31	55
05:00 PM	21	35	30	65
07:00 PM	20	37	29	66
09:00 PM	16	39	24	63

Time	Start	Inv	Ev	ROM
07:00 AM	16	39	19	58
09:00 AM	19	44	29	73
11:00 AM	15	43	21	64
01:00 PM	16	41	22	63
03:00 PM	14	40	24	64
05:00 PM	19	39	23	62
07:00 PM	21	41	25	66
09:00 PM	16	44	21	65

Time	Start	Inv	Ev	ROM
07:00 AM	24	49	16	65
09:00 AM	29	58	20	78
11:00 AM	21	51	17	68
01:00 PM	22	52	21	73
03:00 PM	26	51	19	70
05:00 PM	24	49	20	69
07:00 PM	25	50	21	71
09:00 PM	24	54	16	70

Appendix 1(b).
Axis orientation comparison group data.

t	Start(bisect	Inv	Inv(bisect	Ev	Ev(bisect	ROM	ROM(bisect	InvROM	InvRom(bis
	5	38	36	30	19	68	55	72	41
	5	44	39	19	22	63	61	74	44
	10	24	39	34	16	58	55	68	49
	5	41	32	24	9	65	41	75	37
	5	44	31	18	19	62	50	74	36
	0	45	31	34	19	79	500	80	31
	0	34	35	41	30	75	65	73	35
	5	38	34	44	19	82	53	78	39
	4	39	53	29	25	68	78	68	57
	12	44	46	34	19	78	65	78	58
	8	43	49	24	20	67	69	74	58
	11	15	44	24	19	39	63	53	55
	9	29	44	34	21	63	65	65	54
	11	35	31	39	24	74	55	73	42
	0	44	33	18	14	62	47	75	33

Appendix 1(c).

Pathologies distal and proximal to the ankle joint complex group data.

Start	In	Ev	ROM	Total Inv	Age	Location
25	30	25	55	55	63	foot
30	35	20	55	65	49	foot
20	45	25	70	65	55	hips
15	45	25	70	60	27	knees
20	40	30	70	60	34	foot
25	45	30	75	70	43	foot
20	45	20	65	65	19	foot
20	35	15	50	55	54	ankle
25	45	30	75	70	69	hip
15	45	20	65	60	65	foot
15	40	25	65	55	57	ankle
25	45	20	65	70	36	foot
20	35	25	60	55	36	calf
25	40	35	75	65	60	foot
20	55	20	75	75	16	hips
25	50	25	75	75	57	foot
30	35	30	65	65	47	ankle
20	40	30	70	60	24	knee
15	35	20	55	50	38	knee
25	40	25	65	65	35	foot

Appendix 2.

Shapiro-Wilk test results for control group data.

```
                    Shapiro-Wilk W test for normal data
Variable |     Obs        W          V           z      Pr > z
---------+------------------------------------------------------
   start |     100     0.98707     1.067       0.144   0.44257
     Inv |     100     0.99220     0.644      -0.977   0.83564
      Ev |     100     0.97701     1.898       1.421   0.07760
     ROM |     100     0.99074     0.765      -0.595   0.72410
    Tinv |     100     0.99194     0.666      -0.903   0.81672
```

2. sfrancia start Inv Ev ROM Tinv

```
                 Shapiro-Francia W' test for normal data
Variable |     Obs        W'         V'          z       Pr>z
---------+------------------------------------------------------
   start |     100     0.98709     1.167       0.314   0.37665
     Inv |     100     0.99175     0.745      -0.608   0.72829
      Ev |     100     0.98971     0.930      -0.149   0.55937
     ROM |     100     0.99260     0.669      -0.833   0.79744
    Tinv |     100     0.99325     0.610      -1.027   0.84780
```

3. summarize start Inv Ev ROM Tinv, detail

```
                              start
-------------------------------------------------------------
      Percentiles      Smallest
 1%            7              6
 5%            9              8
10%           11              9       Obs                 100
25%           17              9       Sum of Wgt.         100

50%           19                      Mean              19.08
                        Largest       Std. Dev.      5.020524
75%         22.5             26
90%         24.5             29       Variance       25.20566
95%           26             30       Skewness      -.1932528
99%         32.5             35       Kurtosis       3.672998
```

Inv

	Percentiles	Smallest		
1%	23.5	22		
5%	30.5	25		
10%	32	28	Obs	100
25%	35	29	Sum of Wgt.	100
50%	44		Mean	44.87
		Largest	Std. Dev.	10.82893
75%	52	64		
90%	60	69	Variance	117.2658
95%	63.5	69	Skewness	.246045
99%	69.5	70	Kurtosis	2.311765

Ev

	Percentiles	Smallest		
1%	11.5	10		
5%	14	13		
10%	15	13	Obs	100
25%	19	13	Sum of Wgt.	100
50%	21		Mean	21.52
		Largest	Std. Dev.	5.113816
75%	25	31		
90%	29	31	Variance	26.15111
95%	31	36	Skewness	.4783355
99%	36	36	Kurtosis	3.168537

ROM

	Percentiles	Smallest		
1%	44.5	44		
5%	49	45		
10%	50	46	Obs	100
25%	57	49	Sum of Wgt.	100
50%	67.5		Mean	66.37
		Largest	Std. Dev.	11.23366
75%	75	85		
90%	80	88	Variance	126.1951
95%	83.5	90	Skewness	.0505318
99%	92	94	Kurtosis	2.231943

Tinv

	Percentiles	Smallest		
1%	42	41		
5%	49.5	43		
10%	51	48	Obs	100
25%	56.5	49	Sum of Wgt.	100
50%	65		Mean	63.95
		Largest	Std. Dev.	10.22611
75%	71	82		
90%	77.5	83	Variance	104.5732
95%	80	83	Skewness	-.0033613
99%	84.5	86	Kurtosis	2.105922

Appendix 2(a).

Analysis of Variance test results for diurnal variation group data.

```
> anova(aov(Value~Subject+Time, dh2, subset=dh2$Variable=="Start"))
Analysis of Variance Table

Response: Value

Terms added sequentially (first to last)
          Df Sum of Sq  Mean Sq  F Value        Pr(F)
Subject    6  352.7500 58.79167 21.63975 2.000000e-11
Time       7  128.2679 18.32398  6.74460 2.254191e-05
Residuals 42  114.1071  2.71684
> anova(aov(Value~Subject+Time, dh2, subset=dh2$Variable=="Inv"))
Analysis of Variance Table

Response: Value

Terms added sequentially (first to last)
          Df Sum of Sq  Mean Sq  F Value        Pr(F)
Subject    6  1471.750 245.2917 67.28785 0.000000e+00
Time       7   175.268  25.0383  6.86844 1.876089e-05
Residuals 42   153.107   3.6454
> anova(aov(Value~Subject+Time, dh2, subset=dh2$Variable=="Ev"))
Analysis of Variance Table

Response: Value

Terms added sequentially (first to last)
          Df Sum of Sq  Mean Sq  F Value        Pr(F)
Subject    6  421.1786 70.19643 17.14455 0.0000000007
Time       7  149.4107 21.34439  5.21308 0.0002471813
Residuals 42  171.9643  4.09439
> anova(aov(Value~Subject+Time, dh2, subset=dh2$Variable=="ROM"))
Analysis of Variance Table

Response: Value

Terms added sequentially (first to last)
          Df Sum of Sq  Mean Sq  F Value       Pr(F)
Subject    6  668.6071 111.4345 10.36846 0.000000494
Time       7  324.8571  46.4082  4.31806 0.001120505
Residuals 42  451.3929  10.7474
```

Appendix 2(b)

Shapiro-Wilks and t-test results for axis orientation comparison group data.

```
                  Shapiro-Wilk W test for normal data
Variable |     Obs         W          V           z     Pr > z
---------+--------------------------------------------------
   Start |      15     0.95727      0.829     -0.372  0.64501
     Inv |      15     0.81478      3.591      2.529  0.00573
      Ev |      15     0.95207      0.929     -0.145  0.55761
     ROM |      15     0.91198      1.707      1.057  0.14519

1. swilk Start2 Inv2 Ev2 ROM2

                  Shapiro-Wilk W test for normal data
Variable |     Obs         W          V           z     Pr > z
---------+--------------------------------------------------
  Start2 |      15     0.93414      1.277      0.484  0.31435
    Inv2 |      15     0.89958      1.947      1.318  0.09379
     Ev2 |      15     0.97081      0.566     -1.126  0.86989
    ROM2 |      15     0.98614      0.269     -2.599  0.99532

2. ttest  Start= Start2, unpaired

 Variable |      Obs         Mean    Std. Dev.
---------+--------------------------------
    Start |       15     34.86667     4.323799
   Start2 |       15            6     4.070802
---------+--------------------------------
 combined |       30     20.43333     15.24893

         Ho:  mean(x) = mean(y)   (assuming equal variances)
                    t = 18.83 with 28 d.f.
             Pr > |t| = 0.0000

3. ttest Inv= Inv2 unpaired
invalid 'unpaired'
r(198);

4. ttest  Inv= Inv2, unpaired

 Variable |      Obs         Mean    Std. Dev.
---------+--------------------------------
      Inv |       15     37.13333     8.650901
     Inv2 |       15     38.46667     7.160074
---------+--------------------------------
 combined |       30         37.8     7.831854

         Ho:  mean(x) = mean(y)   (assuming equal variances)
                    t = -0.46 with 28 d.f.
             Pr > |t| = 0.6492
```

5. **ttest Ev= Ev2, unpaired**

Variable	Obs	Mean	Std. Dev.
Ev	15	29.73333	8.362046
Ev2	15	19.66667	4.805751
combined	30	24.7	8.432899

```
Ho:  mean(x) = mean(y)  (assuming equal variances)
           t = 4.04 with 28 d.f.
    Pr > |t| = 0.0004
```

6. **ttest ROM= ROM2, unpaired**

Variable	Obs	Mean	Std. Dev.
ROM	15	66.86667	10.54153
ROM2	15	58.13333	9.605554
combined	30	62.5	10.85881

```
Ho:  mean(x) = mean(y)  (assuming equal variances)
           t = 2.37 with 28 d.f.
    Pr > |t| = 0.0248
```

Appendix 2(c)

Shapiro-Wilks and t-test results for pathologies distal and proximal to the ankle group data.

Shapiro-Wilk W test for normal data

Variable	Obs	W	V	z	Pr > z
Start	20	0.94267	1.357	0.615	0.26913
Inv	20	0.97217	0.659	-0.841	0.79989
Ev	20	0.97706	0.543	-1.231	0.89075
ROM	20	0.94570	1.285	0.506	0.30652
Tinv	20	0.97619	0.564	-1.156	0.87606

1. ttest Start, by (type)

Variable	Obs	Mean	Std. Dev.
1	10	23.2	3.966527
2	10	20.8	5.6921
combined	20	22	4.931104

```
Ho:  mean(x) = mean(y)   (assuming equal variances)
           t = 1.09 with 18 d.f.
    Pr > |t| = 0.2884
```

2. ttest Inv, by (type)

Variable	Obs	Mean	Std. Dev.
1	10	42.1	5.566766
2	10	41.5	6.587024
combined	20	41.8	5.943595

```
Ho:  mean(x) = mean(y)   (assuming equal variances)
           t = 0.22 with 18 d.f.
    Pr > |t| = 0.8283
```

3. ttest Ev, by (type)

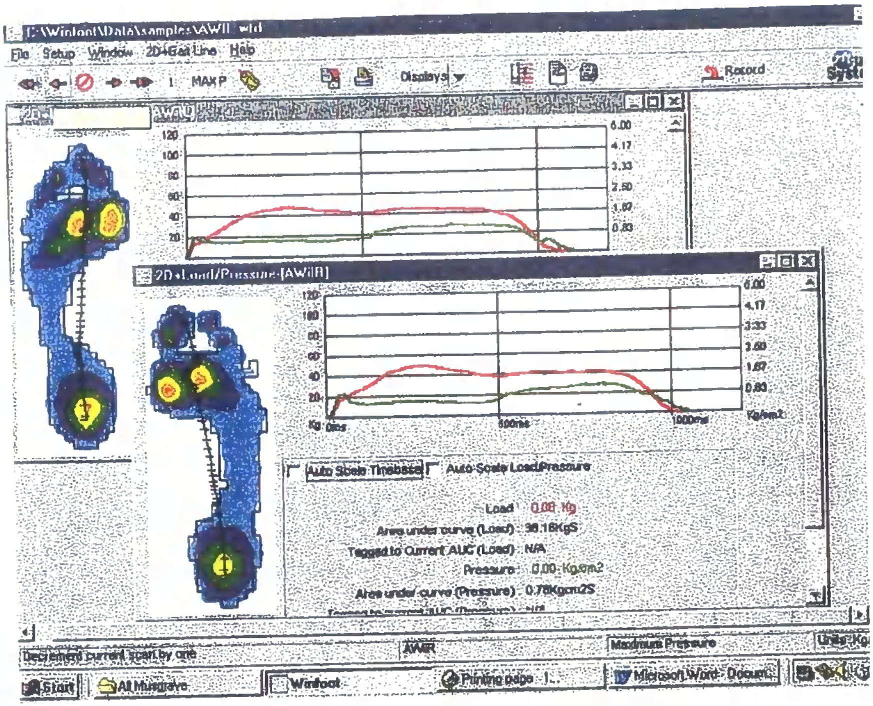
Variable	Obs	Mean	Std. Dev.
1	10	25.4	4.926121
2	10	24.2	5.287301
combined	20	24.8	5.011566

```
Ho:  mean(x) = mean(y)   (assuming equal variances)
           t = 0.53 with 18 d.f.
    Pr > |t| = 0.6059
```

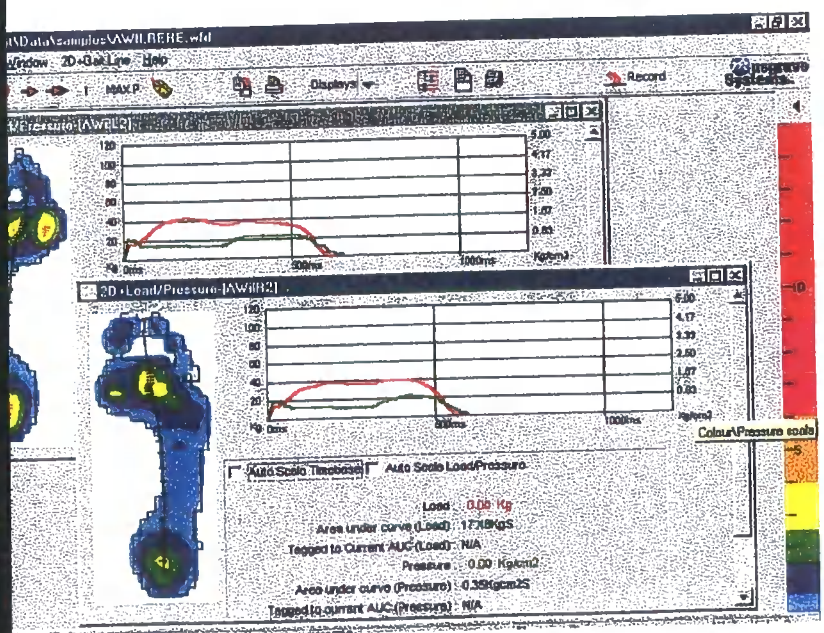
4. **ttest ROM, by (type)**

```
Variable |        Obs          Mean   Std. Dev.
---------+---------------------------------------
       1 |         10          67.5    7.027723
       2 |         10          65.7    7.860591
---------+---------------------------------------
combined |         20          66.6    7.315449

         Ho:  mean(x) = mean(y)  (assuming equal variances)
                    t = 0.54 with 18 d.f.
             Pr > |t| = 0.5959
```



Pre-treatment with orthoses.



Post-treatment with orthoses.

Summary of improvements.

- Bi-lateral reduced force-time integral.
- Reduced loading on both first/ second metatarsal heads.